NIST GCR 90-577-1

POLYMER COMPOSITES

OPPORTUNITIES FOR INNOVATION

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Opportunities for Innovation: Polymer Composites

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FOREWORD

In the world of competitive business, the phrase "technology transfer" has come to mean movement of technological information either from universities or from Federal laboratories to industrial companies capable of translating this information into a commercial product or process. However, it is inter-company communication, formal and informal, oral and written, that accounts for most of the technological information absorbed and utilized by an innovating company. About two thirds of all technological innovations that result in the commercialization of a new process or new product originate outside the company.[1]

Among the written documentation transmitting technological information, unpublished company reports are, by far, the most important source of information. These reports may have originated in companies that are in a position of either a user or a supplier with respect to the receiving company. Oral communication of innovative technological ideas is about half as frequent as printed information. Person-to-person contacts are most valuable in providing supplemental information as follow-up to written documents. The participation in this process of information diffusion and absorption of technological information requires a significant investment of staff time. In some companies, engineers and scientists spend more than 25% of their time acquiring and processing information.

The majority of small companies do not participate in this process fully because of their limited human and material resources. Therefore, these small firms that are manufacturing a single product or a limited line of products, are often unaware of the many opportunities that exist outside their main line of business. And yet, because small companies are frequently endowed with a great deal of enthusiasm, entrepreneurial spirit, motivation, and intellectual capital, they could increase their output of new products given the opportunity.

The series of NIST monographs called "Opportunities for Innovation" has been conceived with the small technology-based company in mind. Each monograph will provide the technical staff of a small firm with a "multi-company" report on the best opportunities for new business endeavors in a technology-driven market. Each monograph will form a backbone for a workshop program keyed to the relevant topic. The workshop concept is to add the elements of oral communication and person-to-person contact to form a comprehensive technology transfer mechanism.

Each chapter of the monograph, written by an expert in the field, focuses on those aspects of a specific technological discipline where new scientific advances hold promise of early translation into technological innovations. The authors point out the gaps and shortcomings in the state of the art that prevent the commercialization of the art and they explain those aspects of recent scientific and engineering development that need further work. The analysis in each chapter covers a digest of the specific technology, a review of current and potential applications and markets, limitations of the current technology, and the needs in equipment, materials, quality assurance, processing, process control, and other aspects as appropriate, in the next 5 to 10 years.

The monographs are written for engineering and technical people. Those in the business and finance communities who have sufficient technical background will also benefit from studying these monographs.

The first monograph in the series of "Opportunities for Innovation" deals with polymer composites, a mature and yet fast evolving technology, finding wide applications in the automobile, aerospace, and consumer goods markets. Other monographs dealing with both emerging as well as mature technologies will follow.

The U.S. Department of Energy through the Energy-Related Inventions Program provided much of the financial support required to initiate this series. The initial topics were selected primarily on the basis of their significance to the national energy situation.

John W. Lyons
Director, NIST

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[1] Thomas J. Allen: "Managing the Flow of Technology," MIT Press, 1977.

PREFACE

The objective in preparing this monograph was to encourage the industrial competitiveness of small businesses. The approach was to attempt to identify the technological opportunities in the polymer-composites industry that a technologically based company could exploit. To achieve this end, a spectrum of composites processing technologies was chosen representing a wide range of technological maturity. Some of the processes (contact/vacuum bag molding, compression molding, and injection molding), having been used for many decades, are more mature processes. Some of the processes (thermoplastic sheetforming) are at the other end of the maturity spectrum and are still in the development stages. Others are seeing a revolution in applications as new materials become available (thermoplastic filament winding and pultrusion) or as new concepts in design are realized (RTM, S-RIM). Thus, the potentials for invention also span a wide range of opportunities, from improving on existing technologies to developing entirely new ones.

Since the objective was not to provide technology that would enable new processors to come on-line, but rather to identify the needs of the current processors that would allow them to expand into new markets or to broaden their existing markets, the question posed to the authors was "What are the technological limitations that need to be overcome to increase your business?" Or, put another way, "If I showed up to sell you something new today, what would I have to have in my briefcase?"

To identify these technological needs, recognized experts with years of industrial experience were chosen to author the various chapters. They were asked to identify the problems and needs, not to propose solutions. So, in some respects, this monograph is a shopping "wish list" detailing the barriers to increased production of composites. It is the job of the insightful, innovative individual to determine the solutions to these needs and thereby capitalize on them.

In addition to the technological needs identified by the authors, the careful reader will recognize that there are many more needs that are not explicitly stated. Reading carefully between the lines will also result in many additional opportunities being identified. For example, the developing processes will likely be amenable to new processing equipment that has expanded capabilities beyond that which is currently available off-the-shelf.

To ensure technical accuracy and clarity, each chapter in this monograph was reviewed by selected personnel from the University of Delaware's Center for Composite Materials. I am indebted to J. W. Gillespie, Jr., R. L. McCullough, R. B. Pipes, D. Steenkamer, K. V. Steiner, and D. J. Wilkins for the many hours they spent reading the draft manuscripts. Although these papers represented a significant departure from the usual academic papers they typically review, their comments were well targeted to the objectives of the monograph.

In addition to the authors and reviewers, Jarda Ulbrecht from the National Institute of Standards and Technology served a pivotal role in the preparation of this monograph. His foresight identified polymer-matrix composites as one of the most promising areas for technological innovation to aid the small- to medium-sized business. Being the lead monograph in this series is an honor.

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Contact and Vacuum Bag Molding Processes: Current and Future Opportunities

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The basic processes used in the composite molding industry which make up the contact molding process—hand layup, sprayup, and vacuum bag molding—are reviewed with respect to the materials used for molding and tooling. Early innovations which have given rise to the industry segment are identified. The scale and distribution of this segment within the overall composites industry are identified from current industry data and private communications. A surprisingly large concentration of materials use and product output is characteristic of this segment. At a time when the concerns for environmental control are increasing performance responsibilities, the industry finds itself poised on the brink of a period of growth which requires an innovative approach to process and materials. The required changes are not without precedent, and the opportunity for new business and services is substantial and necessary. Several opportunities for the fabrication technology are identified and selected strategies for innovation are discussed.

Key words: contact molding; encapsulation; fiber array; impregnation; infrastructure; in-service monitoring; net-shape fiber array; prepreg; powdered resins; surface coatings; viscosity management; VOC (Volatile Organic Compound).

1. Review of the State of the Art

The process of fabricating composites using contact molding processes is presently performed under conditions appropriate for current thermoset, room-temperature cure resins. Usually a single mold surface is involved, although these molds can become very large or complex in shape and may further utilize breakaway segments to allow for undercuts. The majority of parts are completed using manual compaction, and very few exceed 50 psi. There are three major groupings of processes based upon the means to apply resin and distribute the reinforcement and ensure densification and air release.

1.1 Hand Layup

This process utilizes manual placement of cut-to-size reinforcement onto the mold surface. A schematic of the process is shown in figure 1. The resin materials may be dispensed by spray gun using precatalyzed resin or by catalyst injection at the spray gun. Precatalyzed resin may be dispensed by a napped paint roller as well. Distribution of the resin and final compaction are usually completed manually. These operations may be mechanized singly or in part by special purpose saturators, rollout devices, and robotic systems depending upon the nature of the part shape and the productivity required.

1.2 Sprayup

This process utilizes fiberglass in roving form drawn through an air motor-driven chopper. A schematic of the process is shown in figure 2. The chopper is usually mounted above a spray gun

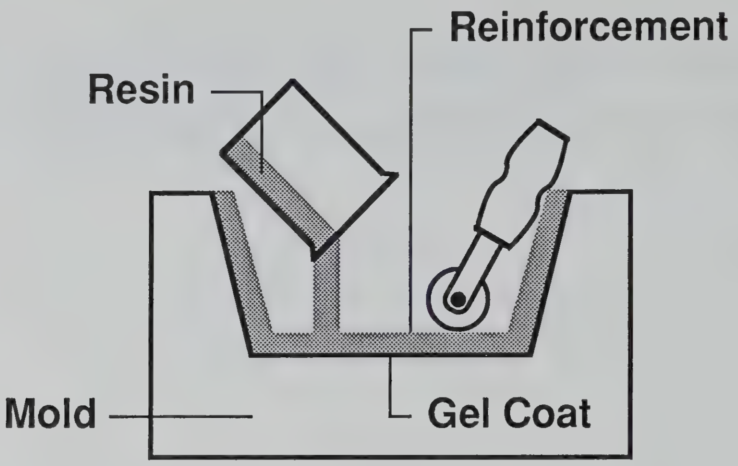

Figure 1. Hand layup process schematic.

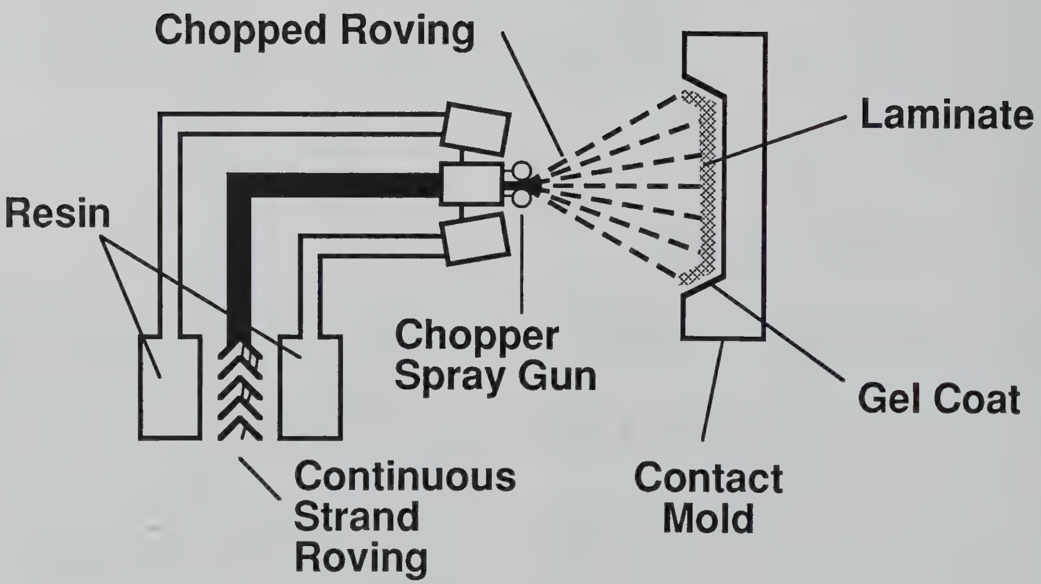

Figure 2. Sprayup process schematic.

which dispenses the resin. The same types of spray guns as used in hand layup may be used. The combined system is usually manually operated and is capable of dispensing upwards of 25 pounds of laminate per minute. Thus labor control and crew balancing are important in operations such as tub shower manufacturing, where this is the predominant process.

The sprayup process may be used on complex mold shapes, but since the fiber is applied in a random fashion, an upward limit of approximately 38% is achieved in fiber content. Therefore, parts are intermediate in strength properties. However, sprayup is often utilized with more oriented fibers via the hand layup process. Considerable quantities of reinforcement are consumed in this market segment. Recent industry estimates indicate that at least 45% of all "E" glass reinforcements used in the contact molding portions of the composites industry are applied by the sprayup process. Thus there has been a continuing effort to improve the performance of the materials and equipment. Robotic application is an obvious extension of the process and will be discussed elsewhere in this monograph.

1.3 Vacuum Bag Molding

This process shares some of the attributes of the hand layup process. A schematic of the process is shown in figure 3. However, since it frequently uses heated molds, ovens, or autoclaves for matrix curing, additional materials, such as prepregs, may be used. Therefore, very high mechanical properties may be realized. There are limitations in design freedom which come about because of the nature of the vacuum compaction process used and the materials which are needed to effect it. In general, parts are not as thick as can be molded in a single mold cycle by hand layup, but there are techniques to overcome this for specific applications such as ballistic armor parts. Alternative techniques for laminate buildup by successive, partial curing episodes are possible if epoxy matrix materials are used. The mold preparation time can be very lengthy on short production runs because of the nature of the vacuum process and the sealing and release systems required. However, this can be substantially reduced with prefabricated vacuum blankets and other accessories for more extended production. It is often the best process when relatively simple, high structural performance and small tooling investments are required. A wide range of materials in prepreg form is available for this process. However, these generally do not include chopped strand fibers. Oriented and woven near-net shape materials are widely available in all commercial fibers.

As in hand layup and sprayup, production rate is a function of the complexity of material placement, and in this case the added effort required for the vacuum material placement. Partial curing for secondary material addition, if necessary, will take several hours, followed by material placement and another cycle on the same mold. Thus, complex parts of very high structural capability may take several days to complete. One part per mold/shift is probably a conservative minimum in the absence of a specific part configuration.

1.4 Other Processing Variants

In the mid to late 1960's, the development of fiberglass fishing trawlers and the initial test work on minesweeper hull sections accelerated development of mechanical methods to saturate or impregnate woven fiberglass broad goods in the 24-ounce per square yard range and combined products of chopped strand mats and woven roving to provide a total reinforcement weight of 37.5 ounces per square yard. Laminate glass ratios of 50% could be achieved, at impregnating speeds of 20 linear feet per minute or faster. Positioning of the wetted, saturated reinforcement was crude, and compaction was by manual methods using the same techniques practiced for hand layup and sprayup. Commercialization of impregnating equipment has followed and material handling has been improved by mechanical positioning of the impregnator relative to the mold. Placement and compaction today still use manual methods. This process variant is used on large boats, barges, minesweepers, barge covers, and other large, relatively simple shaped structural parts. Since woven broad goods can be obtained in very wide widths, impregnators up to 10 feet wide have been built for special applications. It should be noted that although impregnation equipment was originally developed for use at the mold site, attempts have been made to use it to saturate reinforcement for prepregs.

2. General Design Considerations

Detailed design constraints can be found in texts on reinforced plastics and in information supplied by the major reinforcement vendors. An overview is in table 1. In general, this process segment pro-

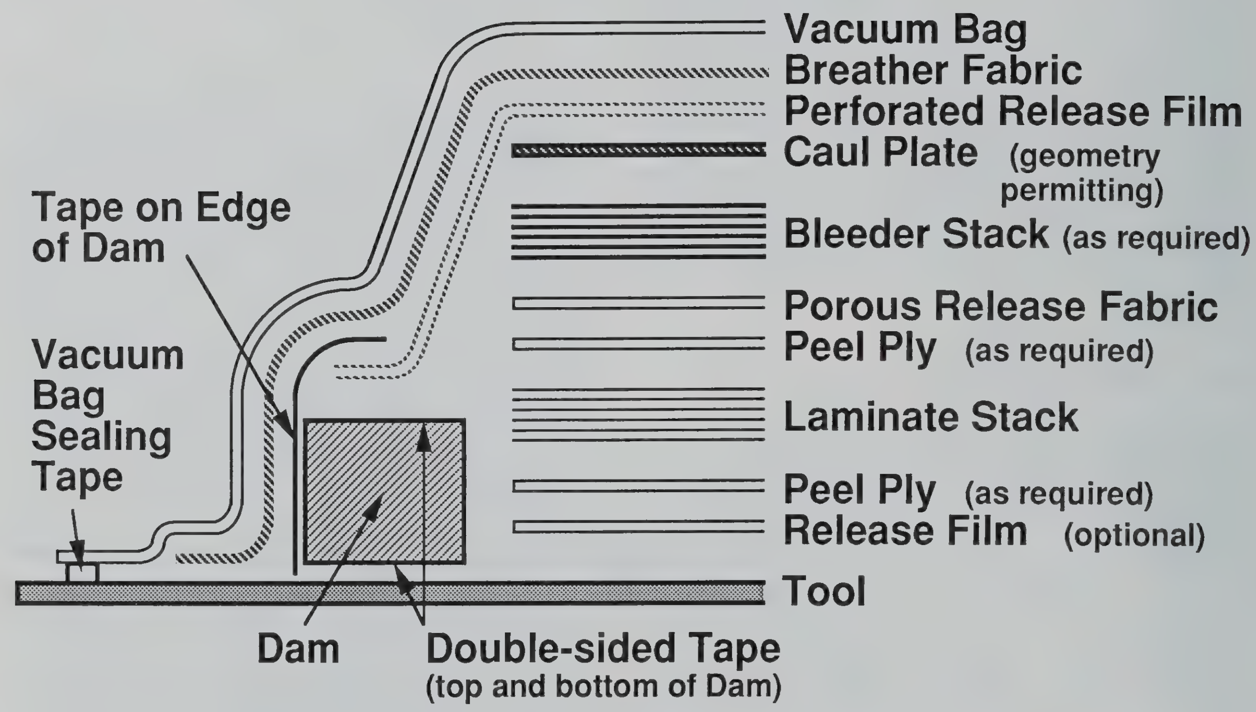

Figure 3. Vacuum bagging/stacking sequence.

Table 1. General design considerations for hand layup and sprayup

Characteristic		Hand layup	Sprayup
Minimum Inside Radius		1/4"	1/4"
Molded-in Holes		Large	Large
Trimmed In Mold		Yes	Yes
Undercuts (Split Mold)		Yes	Yes
Minimum Draft Recommended		2°	2°
Minimum Practical Thickness		.030"	.060"
Maximum Practical Thickness		Virtually Unlimited	Virtually Unlimited
Maximum Thickness Variation		±.020"	±.020"
Maximum Thickness Build-up		As Desired	As Desired
Corrugated Sections		Yes	Yes
Metal Inserts		Yes	Yes
Surfacing Mat		Yes	Yes
Limiting Size Factor		Mold Size	Mold Size
Metal Edge Stiffeners		Yes	Yes
Bosses		Yes	Yes
Fins		Difficult	Difficult
Hat Sections		Yes	Yes
Molded-in Labels		Yes	Yes
Raised Numbers/Letters		Yes	Yes
Translucency		Yes	Yes
Strength Orientation		Random or Directional	Random
Typical Fiberglass Reinforcements (Loading percent by weight)		25-65%	20-50%

vides the widest latitude in part size and shape, the limitation being the molder's ingenuity in placing the reinforcement and removing the part from the mold (or vice versa). One finished surface is typical. This surface replicates the quality of the mold surface and is usually colored with a polyester gel coat. These finishes can weather very well and provide a complete range of colors. Surface texture is available if the mold surface is so configured. Undercuts, ribs, molded-in inserts, molded-in holes, and section change (by selective reinforcement or core material placement) are available to the molder. Mechanical properties can be relatively high, as fiber contents of 55–65% can be achieved depending upon fiber type and orientation. Although polyester resin is the predominant material, vinyl ester, epoxy, and special formulations of phenolic are available. New materials are emerging which include interpenetrating network systems (IPN), urethanes formulated for sprayup, and hybrids.

2.1 Production Rate

The production rate for these two processes is difficult to assess simply, as it depends largely on mold size and structure. However, a tub shower made by robotic sprayup and gel coated robotically can probably be produced at the rate of three parts per 6-hour shift/per mold. A 25-foot express-cruiser hull will usually require one and one-half to two shifts to produce using manual gel coating and a combination of sprayup and hand layup. A minesweeper will require several weeks to mold the hull.

3. Materials

The major materials constituents are comprised of the fibers in various forms, and the liquid thermoset polymer resin matrix. A selection of processes and additives allow these easily transported and manipulated materials to be fabricated into a variety of end products.

3.1 Glass Fiber

The predominant fiber is "E" Glass. The formulation was originally developed in the late 1930s for fiberglass yarns and tows which could be made into insulation for electrical products such as motors and wiring. The fabrics and tapes were impregnated with "sizes" to give better adhesion to the insulating varnishes and better moisture resistance. A chance spill of a catalyzed thermosetting resin onto a sized fabric identified the improved mechanical properties that such a combination could deliver, and the reinforced plastics industry was on its way. Since then, other glass types have been developed for specialized purposes: "C" glass for improved resistance to acids and "S" glass for higher tensile strength and maintenance of strength at elevated temperatures. These glasses were usually formed from batch or marble melt using rare metal bead forming systems and mechanical attenuation to pull the fibers. An alternative, "A" glass fiber, could be made from a window glass type formulation and could be melted and attenuated in a low output, less expensive process. Environmental and mechanical properties of the "A" fiber have generally been lower, although it has proved useful in many applications, particularly in those not subjected to moisture conditions.

3.2 Non-glass Fibers

Non-glass fibers include aramid (Kevlar®, for example), carbon, polyester, nylon, UHMWPE (ultrahigh molecular weight polyethylene), and specialty fibers such as quartz and boron. These materials variously offer lightness, elongation, toughness, high modulus, and radar transparency. The pricing of these materials reflects their performance. Glass fibers will range from $.90 per pound for sprayup "E" glass to $7.50 per pound for woven roving "S-2". Kevlar® 49 costs in the $14 to $20 per pound range, and the UHMWPE Spectra® costs $40 to $50 per pound. One should remember that adjustments must be made for the fiber type, however, as both Kevlar® and Spectra® are much lighter than glass. However, the contact molding segment of the composites industry is currently over 90% in glass fiber and will probably remain in much the same position for several years. The dark horse on the track may turn out to be the carbon fiber made from pitch raw material if an intermediate modulus material of 30–40 million psi can be made.

3.3 Fiber Arrays

All of the fibers may be obtained in woven and stitched configurations. Glass is universally available for sprayup as a continuous roving for input into the chopper gun. Specialty high performance fibers are available as woven goods or tows, the latter suitable for powder impregnation. Knitting and braiding are available for aramid, glass, carbon, and most of the specialty fibers. Non-woven stitched fabrics are widely available.

3.4 Thermoset Resins

Both resilient orthophthalic and isophthalic polyester resins are generally used for products such as boats, bathroom components, furniture, agricultural products, and construction fascia. The more chemically resistant isophthalic resins are used for corrosion performance applications. Other resins are designed for fire retardant applications. Examples are the HET acid type which has a high chlorine content, and the brominated resins which contain bromine. In addition to fire retardancy the HET acid resins provide excellent chemical and heat resistance. The HET acid resin gets its name from the chemical makeup of its polymer. Vinyl ester resins are often used to provide improved mechanical performance at elevated temperatures. The improved resiliency of vinyl ester resin is often required in structural applications to take advantage of fiber elongation characteristics. The polyester resins are the lowest cost, with price per pound ranging from $0.55 to $1.35 for the bis-A resin. The vinyl ester resin costs $1.44 per pound for the general purpose corrosion-resistant grade and $1.58 per pound for the high heat, corrosion resistant grade. General purpose epoxy resins were priced at $1.15 to $1.26 per pound during the same period. However, the hardeners which must be added to the epoxy resins can increase their cost significantly. Aside from their major use in prepregs, where a suitable choice of hardener will allow the attainment of "B" staging conditions, the very low shrinkage of epoxy resins results in lowered molded-in stresses in the part and longer structural life. Many epoxy materials also exhibit improved resistance to caustic chemicals compared to polyesters. In current practice, the reduction or elimination of volatiles from curing epoxy resins offers another advantage—the ability to gain superior mechanical reliability in laminates made with it. However, certain hardeners, notably MDA (4′4′ methylenedianiline) are suspected of being potentially carcinogenic and must be handled with appropriate safeguards. Resin Selection: The selection of an appropriate resin is often a difficult task. The resin supplier can be of assistance, but his guidance will usually start with the consideration of the process to be used, i.e., the method of resin transport to the fiber, and the method used to cure the part. After that definition he will establish the end use performance requirements of factors such as chemical resistance, weathering, water resistance, fire and temperature resistance, and frequently today, environmental impact will also have to be considered.

3.5 Other Resin Systems

Although the resins mentioned above constitute the bulk of matrix materials used in contact molding, there are many additional types for specialty applications and still others which are modified by "mechanical additives," such as fillers and glass bubbles. Among the most interesting of recent market introduction are the so-called hybrid resins, which use acrylic or urethane functionality in combination with a backbone of polyester to gain reduced volatility, improved elongation, and reasonable cure times. Additional work with modified catalyzation of urethane resins has brought them close to consideration for sprayup, where a reduction in available time for manual compaction of fibers is acceptable.

The mechanical additives include fillers to improve shrinkage, reduce costs, impart a measure of fire retardancy, and expand the size of the laminate by implanting controlled microbubbles of "air" via the microbubbles. The latter additive, besides reducing costs, makes the laminate lighter and thicker and thus stiffer in bending.

An additional mechanical additive frequently used in contact molding operations is a core material: such as balsa wood, various non-styrenated plastic foams, honeycomb made of paper, FRP, aluminum, and aramid. All of these materials are used to gain stiffness by separating the outer composite skins and developing a thicker overall laminate. Obviously, a lighter part, of equivalent flexural stiffness, results as well. The nature of the core material restricts its use to rather simple shapes. More complex shapes may be addressed with chemical foams using various blowing agents and by mechanically frothed polyester resin. Additional additives to impart impact resistance have included rubber and elastomer fillers, although these will probably be superseded by improved resin performance.

4. Contact Molding Equipment

Hand layup and sprayup equipment is not particularly capital intensive. The major requirement for process equipment is for compressed air for gel coating and sprayup systems, which require 8 cfm and 18 cfm respectively (airless equipment), and associated air drying equipment. The sprayup equipment itself is in the $8,000 per station range. This equipment is based on the catalyst injection mode of operation. Additional costs are incurred for air movement and control to meet OSHA requirements with current styrene monomer resins. In addition, VOC (Volatile Organic Compound) emissions and local and EPA abatement concerns must be considered. Some supplier testing has indicated that a conventional polyester resin may lose in excess of 6% of its initial styrene during resin application and gel. A suppressed resin will lose much less. The worker can be properly protected under OSHA regulations by a combination of personal protective devices, engineering changes in the shop layout and air handling, and control of exposure time to volatiles. However, these regulations are changing rapidly, and the use of personal protective devices is being restricted to the marine segment of the contact molding industry. Other segments will have to seek alternative solutions. Several of these approaches will be discussed below.

4.1 Vacuum Bag Molding Equipment

Equipment for vacuum bag molding is very simple in its most basic form. Aside from the tooling which must be capable of accepting the temperature required for curing if a heat-cured resin is used, the other needs are a source of vacuum and elevated temperature. Many parts can be molded at one atmosphere (14.7 psi), and many resins can be "B" staged at 250 °F, with a final cure at a higher temperature. The vacuum may be supplied from a pump or via a compressed air ejector device.

4.2 Tooling for Contact Molding

The molds used in this process are almost universally constructed of polyester resins. Polyester gel coats are used for surfacing. The best tooling utilizes resins and additives designed to contribute to crack and craze resistance under the exotherm temperature of the parts that are molded on them. These molds must take and hold a high polish for ease of release and maintenance of an acceptable surface finish. The molds are generally laminate shells which are backed up with structural stiffening to support the weight of the mold and its part in the laminating position. Very few molds are constructed with integral heating systems, although this is possible. Tool life is expected to be 400–800 parts with a proper maintenance and release program.

4.3 Tooling for Vacuum Bag Molding

The molds used in this process generally have been epoxy in order to maintain the dimensional stability required for the parts. In addition, the molding temperature has generally been above the distortion point of the polyester tools used in hand layup and sprayup. Appearance parts are generally not required in most vacuum bag molded parts, and the high surface gloss required of the polyester tooling could not be achieved or maintained. There have been some improvements in epoxy coating materials for tooling which may alleviate this problem. Recently, additional materials have become available which offer an interesting alternative for high heat cure and thermoforming systems. These are the castable ceramics and segmented cast aluminum tooling. Both systems offer additional process capabilities.

5. Historical Perspective of Contact Molding

The contact molding process has been a creature of an early breakthrough in the use of room temperature cure chemistry. The resulting additive systems did not require large investments in equipment for product startup. A variety of additional materials have been developed to further improve the basic process. There has not been another process development of equal magnitude in the interim years. The current conditions of environmental concern, and competition present the opportunity for another change.

5.1 Resins

The contact molding process dates back to the late 1930's, when it was discovered that a mixture of a reactive monomer (styrene) with an alkyd base resin (polyester) could be cured by additional polymerization at room temperature. Before this, the use of the available glass fibers had been limited to heated activation of resins such as phenolics under pressure and in metallic molds.

An additional modification of the initial process was the introduction of paraffin waxes into the polyester resin to ensure a non-sticky, tack-free surface. In quick succession, other additives followed—thixotropic agents to control the drainage of the liquid resin away from the glass fiber until gelation occurred, polyester resin-based gel coats to provide a superior appearance, and other resin additives to modify resin processing behavior, to mention a few.

Although other resins are used in the contact molding process, the polyester materials constitute the bulk of the usage. The relative ease of processing vinyl ester resins and the demand for the performance characteristics that they exhibit in selected applications is increasing their penetration year by year. Epoxy resins have occupied a special niche where higher resin strength or special processing attributes were required.

5.2 Fibers

Until very recently, the primary reinforcement was glass, generally "E" glass. At first it was available only in woven form with weave patterns, weights, and surface treatments (sizes) to suit the weaving process and the requirements for an effective bond between the fiber and the resin matrix. This latter condition was required to protect the glass fiber from self-abrasion and moisture in the atmosphere, and to improve adhesion with the resin to gain mechanical performance and environmental longevity. Soon the glass strands became available as chopped strands in lengths of 1″ to 1.5″, arranged in a random manner. The product was available in weights of 3/4 to 3 oz. per square foot. This product was soon followed by a woven heavyweight product in which the strands of reinforcement were combined to make bundles (rovings), which in turn were woven. The product—woven roving—is available in weights of 12 to 39 oz. per square foot. As might be expected, additional variations and combinations are available today. For example, a minesweeper being produced in Italy uses a combination of woven roving and chopped strands which are stitched together for use with a resin impregnator. One of the most important reinforcement formats occurred with the recognition that the same form of roving that was used for woven roving (and filament winding and preforming) might be chopped and deposited along with the sprayed polyester resin on the mold surface. Thus, the sprayup process was born. This occurred in the mid-1950's.

5.3 Equipment

Aside from the molds required for the process, the basic equipment required for contact molding is rather simple. As a minimum, it is usefully compared to the finishing requirements of an auto repainting shop using the newer catalyzed finishes.

An air compressor of at least 10 horsepower is required, as well as appropriate equipment for air drying. This equipment is needed to perform the gel-coating operation.

If only hand layup is contemplated, resin can be dispensed with felted rollers, and reinforcement may be compacted manually by use of rollers and squeegees. However, this method is usually wasteful and does not lend itself to ease of process or product control. Resin dispensing by spray is often practiced wherein the catalyst is dispensed along with the resin spray. The same type of equipment may be modified to mount a chopper for the fiberglass, thus giving utility for sprayup as well. Equipment for the resin spray and chopper gun will now require up to 18 CFM (for a typical airless sprayup system) or 7 horsepower per spray gun position. In general, most production contact molding operations will utilize 25 horsepower compressors to handle the various items of equipment, as well as air motor-driven sanding and cutting tools required for part finishing.

6. Emerging Technology

Additional items of specialized equipment have started to appear with increasing frequency; these include resin impregnating devices for the broad goods represented by woven roving, vacuum equipment, and ovens or heated impingement manifolds used for prepregs and vacuum bag molding.

Additional investments in ducting and makeup air handling systems are being made with increasing frequency as environmental and workplace standards are mandated by Federal, State, and local governmental bodies.

The opportunity for new process approaches within the contact molding segment of the composites industry is clearly overdue. The segment alone consumes almost 50% of the polyester resin used in the composites industry. It is clearly seen that the investment required is relatively small. The increase in regulation of workplace related conditions will increase the investment and operating costs for all operators. These pressures may force a "shakeout" of many existing molders and possible relocation to countries more tolerant of workplace conditions and emissions. Changes in materials to reduce shop emissions and to improve working conditions, end product performance, and functional competitiveness are required. The challenge will be to do this within an economic context generally attainable by a significant number of existing molders.

Recently, there have been technologies demonstrated that may signal such an opportunity. Hybrid polyester/urethane resins with reduced styrene loss and improved elongation, encapsulated catalysts for control of gelation uniformity, room temperature cure epoxy prepregs, and ultra-wide preimpregnators for very large parts are being introduced. These and other systems will be discussed below as responsive to needs and opportunities.

7. Contact Molding Market

In the aggregate, this market remains one of the major users of fiber and resin materials. This market can participate in the infrastructure replacement opportunity if improvements in quality assurance, and work place conditions can be achieved. The importance of the number of small producers in this market has been recognized by major material suppliers by their forward integration to provide distribution services to the market segment, and to develop new products, or integrate forward as an end product producer in selected processes such as pultrusion. Further modification of materials systems for the contact process market is being initiated by high performance materials suppliers in the form of speciality prepregs.

7.1 Growth Factors

The near and longer term growth potential for this market is impressive. The overall market is expected to grow from 5% to 7% per year, with larger growth predicted for segments of the advanced composites sector. The past few years have seen a significant restructuring of the resin supplier side of the industry, with offshore suppliers purchasing major resin suppliers. Domestic suppliers such as Shell are vertically integrating towards the market through acquisition of molders. Potential for improved profit margins on resin production may be possible through economies of scale and automation. A major market such as the marine sector is one of the dominant factors in the contact molding sector, and its growth, while not completely countercycle, appears to weather the short-term economic "bumps" rather well. The need for continued replacement in the corrosion-resistant market, via infrastructure replacement, should keep that sector in reasonable shape through the next two decades.

Considerable doubt still exists concerning the preferred surface material for the automotive market. At this time, the SMC thermosets appear to be back in favor. The current shapes allow consideration of thermoplastic forming, with the potential for more rapid production if a suitable surface can be obtained. These developments will spin off into the contact molding markets, provided that suitable fiber arrangements can be developed for both appearance and structural applications. These surfaces must be at least equal to gel coats, as resin system developments can improve the environmental performance of the current unsaturated resin systems.

In structural applications, an expanded contact molding industry may find that process improvements allow production of underbody components for the automotive manufacturers as they move to the outsourcing requirements that more models and reduced model runs may indicate.

7.2 Opportunities for Structural Composites

A further assessment of the opportunity for market growth in structural composites has been proposed by SRI International. They consider several of the current commercial markets for composites as mature—e.g., marine, construction, recreational, and corrosion pipes, etc. They anticipate that composites will make relatively sudden and dramatic changes in the automotive industry with the low-tooling costs that materials changes will allow and the reduction in lead times for short-run vehicles. Perhaps these vehicles may not require robotic processes because of parts consolidation and overall efficiencies of structural design. Although high-performance fibers may be used in local reinforcements, it is estimated that this kind of change would create an annual growth opportunity of 40% to 50% for "E" glass fiber. Another factor favoring of this opportunity is that this production will require close coordination with producing plants and should allow domestic manufacturers to maintain a preferred position. If successful, this capability will be extended to other end use applications within the domestic economy.

Other factors will expedite improvements in the contact molding and vacuum bag molding segments. The major growth in advanced composites seen during the early 1980's may be entering a new phase as defense procurement budgets are scaled back. The high-cost materials and processes are increasingly being re-evaluated against improved conventional material. Alternative processes to relieve the bottlenecks and costs of the autoclave multicycle technology are being actively investigated. Lower costs of processing must be achieved so that the next generation of high-performance aircraft emerging from prototyping in the 1990's will be affordable and not remain a technological tour de force. If these objectives are achieved, some analysts foresee a market growth in high-performance composites in automotive and non-automotive markets approaching 71 million pounds by the year 2000.

7.3 Non-Domestic Participation

Of significant importance is the extent to which offshore suppliers have gained participation in these emerging markets and the manner of entry. At this time, the United States is the acknowledged leader in composites design and materials development. The status of manufacturing technology is less clear. Recent acquisitions of major material suppliers by foreign firms provide access to a full range of technology. Japan's DiaNippon Company recently purchased Reichhold Chemical (which, in turn, has purchased the resins assets of Koppers Chemical Division), and CertainTeed is now owned by Vetrotex, a division of Saint Gobain. Technology is impossible to contain, and probably shouldn't be. However, these arrangements make it more imperative than ever that a realistic, significant, and active interface between governmental, industrial, and academic research be directed towards applied manufacturing development in the large structural part sector. This is now the contact and vacuum bag segment of the composites industry. Almost any part of any volume in these markets is at once larger in surface area, usually more complex in terms of fiber array, and of intermediate to low volume as measured by conventional standards of the high-production closed mold processes. Major modifications in process and alternative (and enabling) materials formats will probably be required. These technologies should be developed on a preferential domestic basis.

7.4 Market Size and Segments

A review of the market data for 1987 and 1988 will provide some perspective of the product areas and, indirectly, the process segments. Tables 2 and 3 provide this data (preliminary data for the periods through September for the indicated years). It will be seen that the aircraft/aerospace segment is fairly small, even if one assumes that all of the epoxy noted as "Reinforced-Other" plus the unsaturated reinforced polyester is added together and compared to the marine segment, which is almost all contact molding by hand layup and sprayup. It is estimated that contact molding currently makes up approximately 57% of the reinforced unsaturated resin market. Its portion of the reinforced epoxy process market would probably be significantly less. A detailed review of the 1984 market by SPI and others indicates that sprayup, hand layup, and vacuum bag/autoclaving in the aggregate made up 41% of the reinforced plastic shipments of long fiber end use applications. Since then, the industry has grown by approximately 26% to a forecasted 1989 annual total of 2,716 million pounds of composites of all types.

Table 2. Pattern of consumption of epoxy[a]

	Million lb.	
Market	1987	1988
Aircraft/aerospace	33	34
Appliances/business equipment	90	3
Construction	393	414
Consumer	130	135
Corrosion-resistant products	326	338
Electrical	55	53
Marine	350	375
Transportation	195	202
Other	50	51
TOTAL	1622	1695

[a] Includes resins, reinforcements, and all compound and composite ingredients.
Source: Plastics World, January 1989.

Table 3. Pattern of consumption of reinforced polyester unsaturated

	Million lb.	
Market	1987	1988
Bonding and adhesives	22	23
Flooring, paving, aggregates	21	28
Protective coatings	171	179
Reinforced uses:		
Electrical laminates	50	55
Other	22	30
Tooling, casting, molding	24	28
Export	75	89
Other	33	38
TOTAL	418	470

Source: Plastics World, January 1989.

Aside from the more capital-intensive processes such as SMC, multi-line pultrusion, and robotic sprayup, this sector has relative ease of entry. There are many small fabricators. Table 4 provides an overview of this segment. The largest number of composites molders in all processes are found in eight northern states, California, and Texas. The latter two states make up 30% of the reported cohort. This is significant, as much of the local legislation concerning VOC (Volatile Organic Compound) emissions and efforts to legislate materials controls has originated there. Molders in the remaining states, all above the Mason-Dixon Line and in heavily populated areas, will probably find the costs of compliance significantly increased due to their locations and seasonal temperature conditions.

Table 4. States ranked by number of processing plants

State	No. processing plants
1. California	485
2. Ohio	287
3. Illinois	252
4. New York	244
5. Pennsylvania	210
6. Michigan	203
7. Texas	193
8. New Jersey	161
9. Massachusetts	147
10. Indiana	134

Source: Modern Plastics, January 1989.

Industry data to reach to the individual company level within this segment of the composite industry is not available from SPI. Alternative sourcing is available in part through other spokesmen more oriented towards the needs of this market segment. The Fiberglass Fabrication Association (FFA), a relatively new organization, has been established to support the contact molding segment more directly. It currently maintains a mailing list of some 7,000 names in 2,990 locations. Current listing includes 550 companies as active members. Of these, approximately 135 are suppliers of various types—materials, equipment, or services. Data (see table 5) relative to the dollar volume of sales per company is useful; the contact molding segment has a preponderance of small companies.

Table 5. FFA membership 1988–1989

FFA membership	Annual company sales
78%	under $1,000,000
12%	$1,000,000–$4,000,000
10%	over $4,000,000

Source: FFA

Since the FFA currently includes most of the major marine and many of the bathroom component molders among its members, one can see that this is truly a fragmented business of many small plants requiring minimum capitalization. Although the mailing list of company and individuals has some probable location redundancy, its distribution and frequency by state serves to further identify the nature of the contact molding segment. California, Florida, and Indiana have the major concentrations of contact molders, followed by large concentrations of molders in Illinois, Michigan, Minnesota, Ohio, Texas, Wisconsin, and Pennsylvania. More than half of the remaining molders are scattered throughout the remaining states.

The FRP output per worker in the contact molding segment using manual lamination, augmented by sprayup in a process ratio of 8:1, is reported recently in marine operations in New Jersey. In this marine segment, 12 companies are reported to utilize 450 fiberglass workers out of a total labor force of 1,960 employees to produce 12.2 million pounds of marine laminate per year. One might be tempted to annualize output per person from this data. However, a large number of secondary operations are required in a boat plant to complete the product following lamination. They include yacht interiors, upholstery, engine and fuel systems installation, etc. These operations are atypical of the contact molding segment as a whole, as FRP moldings are most usually supplied to secondary operations at a customer or are complete as molded.

7.5 Supplier Marketing to the Contact Molding Segment

In the past, the FRP molder has been served by a network of distribution and stocking warehouses loosely allied with the major reinforcement suppliers. In the past few years, this changed dramatically as Ashland Chemical Company has bought out most of the private distributors. FRP Supply, a Division of Ashland Chemical, now offers a complete line of materials and sundry additives to molders throughout the United States. This distribution network can be instrumental in bringing new materials and processing systems to the market on a coordinated basis if Ashland chooses to do so.

8. Current and Potential Markets

The contact molding process has few limitations of size and configuration, and this flexibility of choice has led to increased market penetration in large scale projects. As traditional materials systems wear out, and prove to be energy inefficient; FRP Systems have an opportunity for significant additional growth.

8.1 Marine

The marine market has been the major market for contact molding processes for several decades. It remains the largest in terms of long-fiber structural applications and usage of resins and gel coats. In recent years, the domestic fishing industry has started to convert to FRP boats in an accelerating trend as wooden boats deteriorate and metallics become more costly to maintain. This use in the fishing industry is mirrored somewhat overseas, where most maritime countries have active FRP programs, often with government subsidy, to utilize this material for their inshore and near offshore fleets. A few of these countries have already taken steps to modernize their operations by utilizing reinforcement impregnators and installing workplace vapor control systems.

Although many U.S. design and material studies pointed to potentially successful utilization of the material for military application, alternative military technologies delayed this program for many years. As a result, all NATO countries and several Far East countries are operating large FRP minehunters and gaining expertise for future applications. The United States is currently building a class of FRP minesweepers, although after an Italian design. The continued minesweeper program can serve to establish confidence in processes and materials, as well as provide an opportunity for evaluation of newer systems for more efficient production during its later phases. The need to retrofit most surface assets for increased electronic capability, radar transparency, and other functional design considerations is now being addressed. Improved productivity methods and materials, especially for modification of superstructure on existing ships is necessary. These will be large parts, requiring lightness, stiffness, blast overpressure capability, and fire resistance. Ease of shipyard repair and modification will also be required.

Although the design of the current minesweeper hulls made in the United States allows significant utilization of the impregnator, alternative ship designs requiring more bulkheads and stiffening members may reduce this. In any case, much of the ship must still be fabricated by hand layup methods. This must change for the potential to be realized.

Other ship designs based on innovative mission concepts have been proposed by naval architects. These include variations of catamaran designs to reduce wetted area of the hull. The potential for lightness and shape are well suited to composites using hybrid fiber systems for economics consistent with performance. The submarine of the future will probably have a composite pressure hull. Additional hardware will probably be candidates for composites.

8.2 Land Transportation

Aside from the private automobile market, the movement of goods by truck and rail will require replacement fleets of additional, more energy-efficient carriers. Significant penetration has been made into the truck tractor market, and "E" glass composites as shells and skin and core are heavily represented in trailer applications. More abuse-resistant matrix materials such as the thermoset hybrids or fiber-reinforced thermoplastics would reach into the vehicle markets for engineering construction, railroading, and liquid transportation.

8.3 Infrastructure Replacement and Expansion

The United States, and most other urbanized societies, is outgrowing and wearing out its people-supporting systems. Communication systems can be replaced at a cost by advances in technology. No one has devised a satisfactory substitute for a bridge or a municipal water treatment or power distribution system. These systems wear out with time and need to expand with growing population. Participating in solving this problem offers one of the largest potential markets of all available. Some steps have already been taken.

Solid waste disposal gathering lines in most major urban areas of the United States are in an advanced state of disrepair. Concrete sewer pipe failure due to ground shifting, chemical attack, and additional entry is widespread. Earlier brickwork has failed in many locations for the same reasons. Potential pollution of ground water and increased cost of sewer treatment are the result. Traditional repair by excavation and replacement is not available in most cases because of existing structures and roadways. One promising development currently in use for rehabilitation is the expanding thermosetting glass reinforced "sock." Originally developed in Europe, this process uses a thermoset resin-impregnated glass-fiber array surrounding a plastic tube. The folded repair material is delivered to the sewer opening manhole and secured around its edge, and the balance of the sock is pushed and "washed" down the "drain" with hot water pumped from the delivery truck. The pressurized water pushes the sock against the sewer walls, over and around contours, and cures the thermosetting resin in place. A structural, chemical-resistant repair is completed without upsetting the surface features of the neighborhood. Successful use of this kind of technology should pave the way for additional problem solving. These can include on-site building fascia repair and modification, placement of composite, leave-behind retention molds for polymer concrete bridge components, and off-site molded bridge decking and panels for subways. A major cost of infrastructure repair is the cost of delay and rerouting traffic; systems such as these offer a reduction in delay as well as improved long-term performance.

9. Contact Moldings—Future Needs

The opportunities which now are available to the contact molding process segment of the FRP Industry may not be realized without substantial improvement in several key areas. These needs include workplace improvements to attract better workers, and reduce labor turnover, improvement in initiator management and packaging to simplify the equipment and process methods, improvement in resin, fiber interface to gain more reliable mechanical properties, and the development of an alternative form of pre-packaged resin/fiber system to insure that consistent process results and properties of molded parts will be available throughout the industry.

9.1 Liquid Resins

A clean workplace, the possibility of portable work methods allowing major projects of infrastructure replacement, and the mandated reduction in VOC materials all argue for a fresh look at the opportunity for changes in resins.

9.1.1 Liquid Resin Strategies The styrene monomer used in the majority of polyester used in the process market has two functions—as a partner in chain extension and cross-linking in which 22% by weight is usually required and as a diluent. In the latter case, enough styrene has been added to bring the resin to a suitable viscosity for spraying or other mechanical process. In the past, resins have used as much as 42% styrene for both purposes. Currently, California mandates a maximum of 35% styrene. Reformulated resins are working in California and elsewhere. Overall laminating operations may require improved glass size systems, or resin additives may be required to maintain productivity. Other approaches may have more promise.

The use of resin hybrids, such as the Amoco Xycon® material are useful in this way, as they require less styrene to reach equivalent viscosity. A more rapid gelation is possible as well, further reducing styrene.

9.1.2 The Use of Epoxies Room temperature cure epoxies are another alternative, although not a very good one at the present time for several reasons:

a. The ease of processing is not equal to the polyester system.
b. They are more costly, and performance can usually be met on a cost basis more efficiently with the polyester resin.
c. The epoxy materials have their own set of handling problems, as liquid systems can lead to skin conditions in some individuals.

9.1.3 Initiator Management The use of the free radical initiation system assisted by the dispensing of catalysts of the genre of MEKP (methylethyl ketone peroxide) or BPO (benzoyl peroxide) at the time of resin release is the primary mechanism of phase change in the process. Attention to this factor, and its modification, should allow significant changes to be made throughout the process.

a. *Metering of Liquid Phases.* At this time, the initiator (also called catalyst by many within the industry) is pumped in a solvent to the dispensing point. Most recently, this has been an atomizing nozzle, air or airless, external to the resin stream. There have been some exceptions to this wherein the equipment is arranged to introduce the initiator into the resin stream prior to atomization. In the former case, the vehicles used as the carrier solvent have come under concern as potential carcinogens as they are vaporized into the air of the workplace. Thus, in an attempt to maintain the simplicity of the externally atomized initiator, some vendors have brought on the market BPO dispersed in water. These materials do work but require reformulation of the polyester resin additive system to provide satisfactory end product performance.

b. *Encapsulation.* Encapsulation of initiator materials has been demonstrated in the past several years. Improved viscosity control during molding of BMC and SMC and uniformity of cure in prepregs have been demonstrated. To date, the most reliable mechanism for encapsulation release has been elevated temperature. An encapsulated system would allow a resin manufacturer to ship a liquid monopack product having an extended ambient temperature shelf life. Major simplifications in application equipment could be made. Encapsulation release methods must be developed to effect initiation at ambient or low-temperature conditions. Depending upon materials of encapsulation, several options may exist. If styrene is not used as the prime monomer in a resin, additional options exist. Attainment of a fully functional system would allow significant growth in large-scale end use applications such as on-site infrastructure replacement, potable water storage tanks, and shipyards. The same materials may form the basis for a commercial prepreg system, with suitable reinforcement and viscosity modification.

9.1.4 Viscosity Management of Liquid Systems Viscosity control for contact molding has generally attempted to keep the resins in place after spraying on the vertical mold surface. Other methods of resin dispensing have had similar concerns. In each case, viscosities range between 150 and 3000 cps, depending upon whether the resin is being used for manual impregnation or sprayup, or whether it is an IPN with urethane functionality. Wet-out of the fibers, productivity, and laminate quality are influenced in part by viscosity as well. Size improvements and fiber characteristics also play a significant role. However, the author has participated in trials wherein generic polyester resins were modified via thixotropic agents and other methods to produce a resin that could not be poured. Instead, it was like a lump of grease until it was moved mechanically with a roller or a brush. Under these conditions, the portion displaced mechanically became a semi-liquid, and tests indicated that it would wet out a chopped strand mat. As soon as rolling was completed, the resin returned to its previous gelatinous state. A resin system having this capability, coupled with reinforcements optimized for it, would have significant advantages. These include the following:

a) Reduction in VOC loss,
b) Simplified resin metering, and
c) Reduction in resin use.

Catalyzation of such a system would require some changes. A low-temperature heat activated system, encapsulated initiators, or internal injection could be used.

9.1.5 General Comments While most of these suggestions have been directed at liquid polyester usage, they apply to the vinyl ester systems as well. The epoxy materials must be formulated for improved ease of use at room temperature or at the elevated temperature which can be achieved in the lower cost tools associated with this market segment. It is also probable that improved processing methods and testing, and the use of hybrid systems, coupled with high-performance fibers or conventional glass fibers with improved high-temperature sizes, will largely bypass some of the current epoxy systems. If improved methods of dispensing resins and applying curing agents are made available, we should see improvements in resin performance.

9.2 Prepreg and Other Resin Forms

Semi-dry forms of resins containing fibers have been available for many years. These epoxy prepregs required heat to cure, and at least vacuum bag pressure for compaction. Enough tack was available in the resin to enable the plies to be placed against each other and on the mold surface. However, with very few exceptions, molded section thicknesses per vacuum bag cycle were much thinner than the usual practice in wet contact molding. Thus, problems of multiple-ply bonding and productivity must be addressed. However, for the "high value" parts characteristic of the aerospace industry, this initial practice was usable. In recent years, there has been a growing trend to seek systems that would allow lower cost tooling, non-autoclave molding temperatures and pressures, and modified resin systems to support these needs.

Most of the commercial work is still based upon the use of epoxy systems, with companies like ICI and Ciba-Geigy supplying the special purpose materials. The REN Tooling Division of Ciba-Geigy supplies an epoxy laminating resin which cures at room temperature for 4 days and then is post-cured in an oven. Materials of this type can be made into prepregs and shipped and stored under lowered temperature conditions as is the current practice. The long gel and cure period of such a material would allow a wide range of section and fiber placement options in the contact molding process segment. Tooling using this system can stand elevated temperature cure ranges of 350 °F. The Hexcel 820 resin is another current example. To quote a recent supplier advertisement, "This...breakthrough is remarkably clean, containing no MDA or other toxins and reduces much of your plain, old mess."

The traditionally high cost of conventional prepregs has been one of the reasons that they have found little application in the non-aerospace market segments. This may be mitigated somewhat by reduction in ventilation costs by using a prepreg. Some studies have shown that airless spray deposition of resin may contribute as much as 25% of the total styrene loss when using conventional polyesters. A polyester prepreg, even one using styrene as a monomer, would significantly reduce styrene loss in contact molding. Several options exist to further reduce monomer loss from such a prepreg. These can include handling underneath a transparent barrier sheet, the use of heavier and more comformable fiber arrays by virtue of improved impregnation of lower viscosity resins, addition of DAP to form a monomer blend, and the use of surfacing additives.

9.3 Fibers

Fibers and fiber arrays in the contact molding segment of the process market are predominantly "E" glass, and strand and roving products used in the form of chopped strand mats, woven roving, sprayup chopped roving, and woven cloth products. Specialty products such as knits, nonwoven stitched products, and a growing list of special fiber arrays to achieve oriented strength properties and mold conformability are increasingly used.

Further improvements in fiber properties arising from the needs of the aerospace industry will offer increased opportunity for market development in structural applications. These include sizing improvements made on glass fibers where "E" and "S-2" are now able to operate effectively above 350 °F. Carbon fiber made from PAN precursor materials is currently in a market glut condition, with more capacity coming on stream. Department of Defense requirements for domestic sourcing, coupled with a probable leveling of defense procurements, should bring down the cost of the fiber in the near future. The increasing utilization of the newer high-performance, ultra-high molecular weight polyethylene fibers such as the Allied Spectra® material will provide additional market opportunities for new end use applications. Spectra® does have some processing difficulties, but some techniques have been developed to prepreg the material with thermoplastic elastomers as well as with thermosets.

In both contact molding using manual compaction or by vacuum bag molding, a need will emerge for increased availability at lower costs of the special fiber arrays now made by stitching. In addition, the rate at which thermoforming preform processes are being reintroduced in RTM and SRIM will support attempts to preform for fiber conditioning for contact molding, with additional opportunities for custom or at-site prepregging. The long open time tooling resins discussed elsewhere in this paper are currently available. Several secondary convertors have supplied systems for temporary fixation of fiber arrays. These use resin compatible networks or planar arrays of netting that can dissolve in the resin. One current product is marketed by the Anchor Reinforcements Unit of Air Products and Chemicals, Inc., Allentown, Pennsylvania. These "fixative" systems, coupled with computer-aided continuous and/or cut strand robotic placement, would allow development of formable isotropic fiber arrays. Using longer lengths of cut fibers, mechanical properties greater than those achieved by chopped strand mat and sprayup may be obtained. Conventional roving fiber arrays typical of the woven and stitched methods may be achieved. Textured rovings to achieve intra-ply shear strength may be more easily utilized in this way, as they are difficult to process in weaving operations.

Improvements in the mechanical and physical properties of reinforcement fibers and sizes have been numerous in the past years. This has been especially true in the high-performance markets. Commodity fibers, largely "E" glass, have remained relatively stable, with improvements coming from size systems for improved process performance and end use qualities. Some changes in the nature of the fiber array through mechanical processing (weaving, stitching, etc.) have been directed at major markets—notably marine and sporting goods. In most cases, these innovations have occurred at secondary suppliers such as weavers or other converters. These companies will look for niche opportunities. The escalating costs of fabrication and the requirement to complete the product in less time to reduce VOC emissions and worker exposure will provide them with an additional sales argument.

The ability to fabricate reinforcement arrays in the shape of the part is being used to gain production economics and improvements in in-plane shear. Braiding, circular knitting, and other textile processes are being used. Some in the industry believe that this approach will provide a basis for prepregs which will be more cost effective and reliable than the current generation of computer-controlled tape laydown machines such as those used for aerospace parts. This is not our interest, however, to the extent that high-performance structural moldings may become candidates for infrastructure replacement elements or unit moldings; the capability that three-dimensional fiber arrays offer to the engineer and molder should be closely monitored. Least-cost fabrication methods to "fix" fiber arrays should be developed.

9.4 Combined "Prepreg-like" Materials

Aside from the partial gel characterized as "B-staging" in the epoxy, and the impregnation of fibers by the resin matrix, the prepreg is normally a high viscosity material requiring a significant temperature rise to lower its viscosity for conformability and further fiber wet-out. These latter factors are frequently at odds with each other and are among the reasons for the continuing efforts in void control and the limitations on thickness buildup per molding cycle. There may be other mechanisms to be used in achieving the materials handling advantages of the increase in viscosity following fiber wet-out.

The contact molding process and materials place a premium on the ease of fiber wet-out with current materials. A reduction of styrene percentage or the use of alternative monomers will probably still meet with these requirements by industry molders. A conventional SMC compounding line such as made by Finn and Fram can be used to process polyester resins (and vinyl esters) to provide either uniaxial, chopped, orthotropic, or broad goods wet-out that is equal to that achieved by airless spray and manual rollout. A rapid viscosity increase to hold the resin in place is required, but this increase must be self-capping. It has been demonstrated that selected SMC thickening agents, singly or in combination, have the ability to create suitable viscosity changes which will remain stable at room temperature over a period of several months. When low-temperature initiators are used or when UV cure initiators such as supplied by Ashland Chemical and BASF are incorporated in the resins, a suitable cure may be realized.

This type of system would allow a resin or fiber supplier to market a monopack to his customers. The large molder could make his own "prepreg" in house. Recent reports of impregnating equipment to be marketed by Binks Co. indicate that additional suitable equipment may be available. Ashland Chemical has also selectively marketed wet impregnation equipment for its specialty marine resins. This system is used at the laminating site in conjunction with long open time, room temperature cure resins.

The change to a combined material in a prepreg-like form will probably preclude manual compaction, which is the norm for most contact molding processes. Thus the more highly configured parts such as tubs and showers, detailed building fascia, and small consumer parts may not be directly responsive. The larger parts, including those which have a more moderate degree of shape configuration, can be candidates. The advantages of better control of mechanical properties and tighter dimensional control that low-bleed prepregs will give, along with reduced VOC losses in the larger production areas should prove of economic benefit. The placement of specific, optimum fiber/resin configurations within the part area and section thickness as functionally required is more certain and controllable with the integrated combined material system. The further ability to use fillers, cores, and other fastening and hard points is not compromised. The fabrication of large appearance parts may be a challenge due to the need to control exotherm with the polyester prepreg. However, by choosing alternative viscosity modifying systems, one is not limited to the polyester or vinyl ester systems. In addition, several other strategies exist—cored tooling, higher heat distortion gel coats or alternative gel coats, or longer production cycles.

9.5 Alternative Monomer Systems

The increasing concern about, and more widespread legislative control of, workplace materials and releases to the atmosphere highlight alternatives so long as thermosets are considered. Of the many monomers which may be used, DAP (diallyl phthalate) has recently been used in a polyester prepreg for thick-section ballistic moldings where the styrenated prepreg was undesirable on a local use basis in California. The DAP monomer will require a somewhat higher cure temperature, but it has lower volatility. It also has lower shrinkage, so it may be helpful in improving appearance parts. An alternative approach to the monomer system is found with the class of materials that are the so-called "solid monomers." These materials can be used with polyesters and other free-radical cross-linked polymers. They have no volatility in the temperature ranges in which they would be used for composites. As prepregs, they would be processed much as a hot melt. At room temperature in a polyester resin such as an isophthalic, they would contribute extended shelf life at ambient temperature. An early example of this monomer was DAA (diAcetone Acrylamide). This has been replaced with a second generation product system, AMPS (2-acrylamido-2-methylpropanesulfonic acid). This material will cost less than $2.00 a pound.

The significance of a change in the physical format and dispensing method of the matrix resin cannot be overstated. Environmental concerns have been approached by additive and chemical tinkering and by installation of increasingly costly ventilation systems. Neither approach does anything to improve productivity, product reliability, or the quality of the workplace. Several possible areas of direction with regard to resin changes have been identified. It should be noted that many of these are compatible with the chemistry of the resin of choice. Several of these changes may be demonstrated and commercialized without extensive resin redevelopment. Further improvement would surely benefit from resin development.

9.6 Surface Coatings

Since the introduction of the polyester appearance gel coat in the 1950's, there have been many improvements in the appearance coating used in the contact molding segment. In spite of its many shortcomings, the system has not been displaced. With molds of high surface quality, and when applied by well-trained personnel, the gel coat will result in a finish that is difficult to match in any other way. However, in recent years, one segment of the contact molding business has experienced appearance problems with the gel coat system. The marine market, after nearly two decades of relatively trouble-free use of the gel coat process, now finds itself concerned with a small but highly visable percentage of products having appearance/blister defects after exposure in water service. The causes have been debatable since they are sporadic, but careful tests have identified several factors of materials and application that lead to the problem. Gel coating with polyester resins is a production cycle controlling operation in most contact molding operations. It is very operator sensitive and is responsible for a significant amount of the VOC emission from a plant fabricating boats or bathroom components. It is cycle-controlling, in that the gel-coat resin must reach a partial cure before additional lamination operations can begin. There are other economic trade-offs inherent in the use of the current gel-coat materials, and the evaluation of these may justify use of alternative technology.

Urethane-based resins were tried as sprayup materials several years ago. Their speed of reaction severely limited reinforcement choice at the time. Since then, additional development has enabled resin blends and catalyst modifications to extend open time enough for consideration as coatings and with some reinforcements in specialized molding situations. One current gel-coat substitute is reported to have excellent water resistance and very short ambient temperature cure time. Lamination can begin almost immediately—it is claimed. Reported compatibility with current commercial laminating resins is also suggested. A candidate urethane sprayup system from Mobay, Aqualast®, is reported to reach a tack-free gel state in 30 seconds. While suitable for a minimum rollout product such as architectural fascia and perhaps tub showers, the short gel time would make it difficult to work on larger parts or multi-ply laminations. Additional resin development is required to further lengthen the open time before gel for use in the manual compaction contact molding operations. The use of these materials as coatings will, however, allow them to be evaluated under operating conditions. If they prove reliable, their use in lamination operations for consumer products, especially sporting goods and construction items, will accelerate.

The desire to use elevated temperature curing in vacuum bag molding, which ceramic and high-temperature epoxy prepreg tooling will bring about, also opens the door to the use of powder coating systems. Polyester powder for electrostatic coating of metal tooling is currently available for sanitary-ware SMC. Non-conductive tooling materials may be made conductive by several well-known techniques, and the melting point of one candidate coating material is low enough (131 °F) for early consideration. Each of these systems offers an opportunity to review the performance potential and overall economics of a reduction in VOC, improved workplace conditions, and improved productivity.

10. Quality Assurance, the Basis for SPC and SQC

The contact molding and vacuum bag process segments produce a range of applications that increasingly include high-performance products. Examples are minimum weight pleasure boats, high-speed water jet skis, corrosion-resistant applications, and potentially major parts of infrastructure replacement elements such as bridge segments. Naval vessels for minesweeper use and other duties are currently under construction or planned for the future. Control technologies that are appropriate to the scale of the manufacturing operations within this manufacturing segment can utilize many of the current technologies developed for other segments of the composites industry. However, attention may be given to more specific concerns.

The contact molding segment, with the exception of perhaps the tub shower molder, does not produce large numbers of serial products. Thus control and quality assurance of individual, usually rather large, items is required. Frequently the molding operation extends over several days and, once started, cannot be aborted. It has been demonstrated that fiber resin ratios can be maintained in manual operations of spray resin deposition within 10% of nominal—by effective shop management. The instrumentation available today measures fiber ratio accurately enough, on finished parts or partial ones. This is not much help on a partially completed 2,000-pound lamination pass in a minesweeper. The present solution is to cut a piece of the saturated material and weigh it, while everyone waits on the outcome. That is the reason that room-temperature prepreg materials or alternative resin formats have such a power to transform this industry. The advanced composites (read aerospace) industry has been able to inspect quality into its product. This is changing; it has never been applied with the same emphasis to the contact molding industry, except in a visual and self-disciplining sense. Fiber/resin ratio is a primary process control objective. Its attainment lies within the materials and equipment design. Historical records can document results and can lend dimension to the efforts towards process improvements.

10.1 Cure Factors

One of the critical factors in thermoset processing is the "cure" condition of the resin matrix during the molding process and in any following steps which may include adhesive bonding to other assemblies. Much attention is paid to the catalysts used, other additives to aid initiation, mold or ambient temperature, and frequently humidity. However, careful evaluation will identify other equally important factors in thermoset molding. These include the size system on the fiber, resin reactivity—especially in long or low-temperature gel time conditions, and the effect of processing additives such as fillers and internal release agents. These effects generally will be compensated for in most shops by catalyst changes or selections to give a reasonable "demold time and hardness (Barcol)." However, comparison of laminates using currently available thermal analytical equipment in any of several modes will indicate that the results are not equal and may lead to change in product performance. Therefore, the molder in the future must concern himself with ensuring that input materials have a known pedigree and "recent bill of health." The resin suppliers can do part of this, and the reinforcement suppliers can attempt to assure the molder that their product has not changed, but each of them buys additives from third parties. The molder must do some of the control himself. There are several areas of testing technology that may be "repackaged" for this segment of the industry.

10.2 Instrumentation and Process Control

The instrumentation opportunity probably exists for cure characterization of liquid thermosets on a more sophisticated basis than is offered by the standard ASTM gel time and peak exotherm tests. Dielectric analysis has been utilized for several years in compression molding operations. An SPI [1] paper discussed Dynamic Dielectric Analysis (DDA). DDA is used to indirectly characterize liquid polyester cure rate and exotherm profile, with extension to the solid phase. Except for a special probe design, the equipment appears to be standard laboratory grade instrumentation. This approach may be used in conjunction with more sophisticated thermal analysis equipment capable of DSC (differential scanning calorimetry) or DMA (dynamic thermomechanical analysis) to establish primary process and material standards for the product to be produced. If reliable correlation can be established for the simpler DDA equipment, the molder may be able to establish materials variation limits on the input materials. Thermal analysis techniques are being further simplified as well, with throwaway sample holders and interface with personal computers (PCs) now common in most businesses. Another approach which might be considered is to offer a testing and analysis service. A major distributor such as the FRP Supply Division of the Ashland Chemical Company could evaluate this possibility. Communication via modem might allow data acquisition at the molding site, with processing at a central or regional location having more sophisticated software and processing capability.

The items described above are not intended to overlook the additional, more common, techniques of coupon testing and structural proof-of-product testing, as well as the normal measures of material and productivity. However, there remain additional opportunities for quality assurance in the product as it performs in service. As mentioned above, a large portion of the future opportunity for this segment of the composites market will be in the replacement of the infrastructure. This will include bridge parts, tanks, ships, construction parts, etc. Parts in the process industries will have to be replaced as well. Techniques will be needed to evaluate the structural condition of the composite part after a period of service, perhaps after being a part of a natural disaster. Acoustic emission testing is one well-known method, but it is frequently difficult to utilize and interpret. Recent use of optical fibers in composite aircraft components to monitor strain and laminate damage should be directly applicable. This type of system would lend itself to a specialized service business where the installer would work in consultation with the molder. Alternatively, dedicated reinforcing and optical fiber arrays might be marketed as a prepreg, with an appropriate standard of installation and annual testing. In the case of a bridge, large tank, or ship section, the service performed would be like that provided by the American Bureau of Shipping—worldwide.

11. Additional Productivity

The contact molding segment of the composites manufacturing industry will require increased domestic productivity to match landed costs of similar imported products. The materials are available in most countries, and many countries currently have neither the increasing labor costs nor the increasing costs of environmental compliance of the domestic sector. Petrochemical feed stocks from which the basic resins are produced are also readily available to the Pacific Rim and South American countries. European competition is more likely to be on par with the United States, as most of the same supply and environmental concerns apply. However, European countries, primarily the Scandinavian sector, have struggled to cope with open mold environmental issues in a more dedicated manner than has been the case in the United States.

Engineering solutions to the styrene emissions in contact molding shops were initiated several years ago in Sweden and Norway. However, until recently, there has been relatively little emphasis on external shop abatement. Early attempts at using programmable robots for sprayup have been reported, as well as processing under vacuum. In 1970, Owens-Corning Fiberglas demonstrated robotic sprayup [2] at its Granville, Ohio, laboratories. The then state-of-the-art "robot" could be made to satisfactorily spray up a small boat and a shower stall, and preform a small riding mower. However, shortcomings in the accuracy of resin pumping systems, the requirements for alternative drive motors for the glass choppers, and the requirement for a large supply source of reinforcement at the work position were among the needs identified for future work. The increased emphasis on reduction of worker exposure to styrene has brought robotic sprayup to attention once again. There are other advantages besides elimination of direct labor. Output is much faster, and thickness control accuracy is improved. In states where local VOC levels have been mandated, reduced emissions by more efficient production may allow more production. This equipment is costly, ranging in installed costs from $80,000 to $200,000. It should be noted that relatively few product types are made completely by sprayup. Compaction of sprayup is by another robot or, more likely, done manually. However, those products that are primarily sprayup include the one-piece tub showers and many recreational products such as jet skis and snowmobiles. It is probable that the robotic systems may also be used to prepare materials for further processing as discussed elsewhere in this report. A universal application of the robot is in the gel coating operation. The rapid gel and high-performance potential of the urethanes may not permit manual operation with its inherent variability. These operations are very similar to automotive and truck painting requirements, and there should be relative ease of transfer if economically feasible. Another area in which the robotic device may be used is in conjunction with high-intensity UV cure systems. Thicker laminations may be processed and the safety problems and illumination angles may be more easily managed for complex parts in this way.

Alternative, innovative resin formats, as well as existing resin formats may be processed in a second generation of reinforcement impregnators or saturators. Venus-Gusmer was among the first to commercialize this equipment and will be followed by Binks. However, neither machine will impregnate reinforcement without entrapping some air, nor dispense cut lengths without resin drippage. Still, the capacity of the present impregnators far outstrips the capability of the laminating crew to place and compact the material.

The alternative resin and fiber formats will provide the opportunity to develop additional processing methods. For example, encapsulated catalysts will require only mixing in the master batch of resin or metering from a resin admix. Initiation of cure will depend upon the technique used to break down the encapsulation material within the temperature range of the molding method. The encapsulation material must protect the initiator from the resin for an extended period. These are the technologies that must be developed. One might consider a technology that would open a greater or lesser number of encapsulant "particles" to provide the proper cure conditions for the ambient temperature and laminate mass.

Vacuum bag molders will have an opportunity to use high-temperature tooling through use of ceramic and new high-performance epoxy materials. These tooling materials will allow use of both high-temperature cure thermosets and the molding of thermoplastic materials such as the recently introduced thermoplastic powder prepregs produced by BASF. The same technique can work with some thermoset materials in a powder form. Both formats result in low to zero solvent loss. Commercial products in carbon, "S-2" glass, and quartz fibers are available. A lower cost material system may be postulated based upon a powder utilizing a flake polyester and a solid monomer such as the AMPS solid monomer.

The contact molding and vacuum bag molding segment of the industry may be pregnant with potential for process change. Robotic operations for sprayup will proliferate without a doubt and can make use of the current liquid polyester resin systems. However, increased emphasis on optimization of design for structural performance and weight in all end use markets serviced by these processes will require mixed fiber arrays, which may reduce the impact of robotic materials placement to offset labor cost and worker exposure to volatiles. The size of the overall market is such that changes in resin systems to move towards room-temperature handleable prepregs and low-temperature initiation procedures should find a ready market if properly marketed with supporting technical data. These data must identify relative VOC, mechanical properties under representative initiation techniques, and a package of technical support activities. These activities may be undertaken as a joint venture by an entrepreneur working with a basic resin and/or fiber producer. Resin system modifications will offer an opportunity for equipment design to provide new capabilities to the industry.

The contact molding segment may start to embrace more of the thermoforming technology towards the end of the planning horizon, especially if low-temperature formable thermoset prepregs become available. Several strategies for thermoset/thermoformable matrix systems can be considered. This potential will be increased if alternative fiber arrays and "fixative" methods are developed which will allow three-dimensional forming. Thermoformable materials will also be available.

12. Acknowledgments

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Compression Molding

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Materials and processes for compression molding Class-A components are briefly described. The thermoset resins, fillers, reinforcements, internal mold releases, initiators, low profile thermoplastic additives, thickening agents, pigments, and colorants that are mixed in a predetermined sequence and allowed to maturate to a non-tacky state as molding compound are discussed. Equipment and processing steps to make and mold the compound, the role of molding parameters such as temperature, pressure, velocity, charge shape and its placement, secondaries, and finishing are described. Well-known automotive applications are cited for reference. Areas where advancement in materials, equipment and process technology that can benefit both the molders and the end users are explored.

Key words: Class-A SMC; compression molding; low profile additives; low shrink resins; SMC; SMC materials; SMC process; thermosetting resins.

1. Introduction

In 1908, Dr. Leo Hendrick Baekland formulated the first synthetic molding material, known as Bakelite, which many consider to be the first generation of sheet molding compound (SMC). Numerous technological advances made over the last 8 decades in materials as well as in process areas have propelled the use of SMC to new heights. However, none is more significant than the introduction of composite materials in external automotive body panels. Since then, sheet molding compound, which is a thickened or "B" staged preimpregnated, reinforced, resinous sheet that can be cut and press molded, has become a major material of choice in high volume applications.

In compression molding, a premeasured weight of SMC is placed in a heated mold, the mold halves are brought together and the material flows under pressure to fill the cavity. The part is then removed upon curing of the material. The idea here is to mimic steel stamping and attempts are made to speed up this process, as discussed later, to achieve cycle times of 1 minute or less. While steel parts are stamped faster than SMC components, parts consolidation and molding large complex shapes are possible in SMC. Other advantages of SMC include corrosion resistance, light weight, design flexibility, dimensional stability, and little or no material waste.

2. Materials and Process

SMC is made up of thermosetting resins, inert fillers, and fiber reinforcements. A typical compound for exterior automobile panels contains 25% to 30% by weight organics, 45% to 50% calcium carbonate, and 25% to 30% glass fiber. Particulate filler is replaced by glass fiber if higher strength is needed. A brief description of each of these components, as well as the role of other additives, is given below.

2.1 SMC Materials

A typical SMC formulation and how it is introduced during compounding is shown in figure 1. The most prevalent resin used is unsaturated polyester which, upon crosslinking with styrene, acts as a binding matrix for the fiber reinforcement and other materials. The choice of resin depends on the end use. Phenolic resins are used in ballistic applications, while vinyl esters may be used in some structural parts.

2.1.1 Low Profile Additives The most significant development in SMC technology is the introduction of low shrink resins or low profile additives (LPA). These resins are usually made by adding a finely dispersed or dissolved thermoplastic such as polyethylene, polystyrene, polymethylmethacrylate, PVC, copolymers of styrene, copolymers of methacrylates, polyvinylacetates, polycaprolactones, cellulose acetate butyrate, cellulose acetate propionate, and others to a highly reactive thermosetting resin such as unsaturated polyesters. While the thermoset resin phase is always continuous, the thermoplastic phase may be either discontinuous or continuous following cure of the thermoset resin. The most effective LPA's are soluble before cure and precipitate to a continuous phase. These compounds are used for Class-A body panel applications, as they offer reduced shrinkage and a smoother surface. Generally, the LPA is sold as a styrene solution. It may be sold separately or combined with the thermoset resin solution as a one-pack system. The two-component version offers more flexibility to the molder in controlling the ratio and, thus, the shrinkage. By using LPA's and manipulating filler content, a formulation can be developed with zero or even negative shrinkage. A typical SMC formulation is given in table 1.

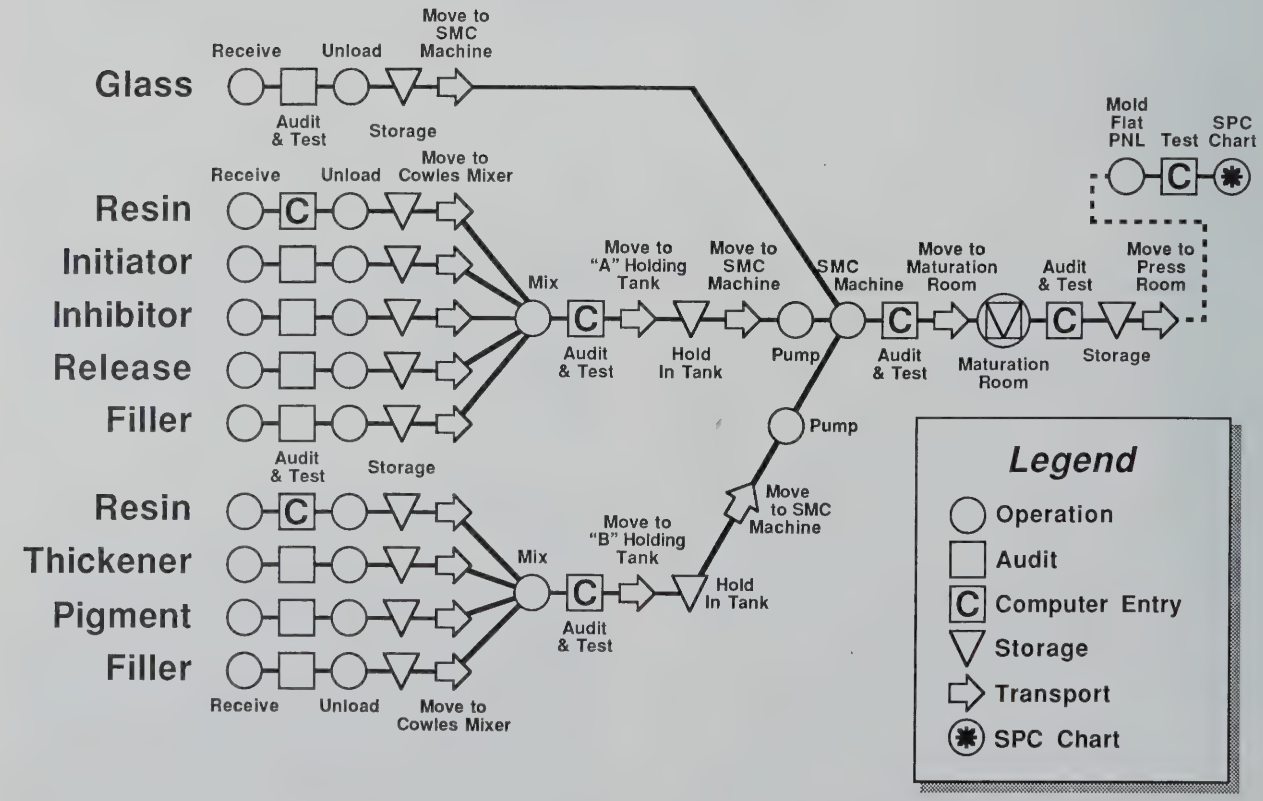

Figure 1. A typical SMC materials process flow chart.

Table 1. Typical SMC formulation

Organics	27%	
Glass Fiber	28%	
Filler	43%	
Misc. Additives	2%	
Polyester Resin	65.0	100 parts
Low Profile Additive (Resin)	35.0	
Initiator	1.0 PHR*	
Internal Release	4.0 PHR	
Filler	150–200 PHR	
Pigment	0.1 PHR	
Thickener	3.0 PHR	
Glass Fiber	25% of SMC total wt.	

* PHR (parts per hundred resin)

2.1.2 Reinforcements The type and amount of reinforcement depends on the desired mechanical properties needed to meet the design and economic requirements. While 1-inch long chopped E-glass fiber (see fig. 2) is the most commonly used reinforcement, other materials such as S-glass, graphite, Kevlar®, etc., can be used in continuous as well as chopped form. Some structural applications such as bumper beams may utilize unidirectional glass roving along the bumper's length for added flexural stiffness. Patches of woven roving, cloth, or continuous strand mat may be used for local reinforcements. Random chopped strand mat also has been used in some Class-A automotive parts.

2.1.3 Fillers Fillers are added for dimensional stability, lower cost, improved stiffness, and enhanced surface smoothness. The most commonly used filler is calcium carbonate; however, hollow microspheres, hydrated alumina, clay and other fillers are used, depending on the application.

2.1.4 Thickeners Certain alkaline earth oxides, hydroxides, and other chemicals are used to thicken the polyester resins to a tack-free moldable state. The divalent earth oxides or hydroxides react with the terminal carboxyl groups on the polyester chain resulting in increased average molecular weight of the resin. The thickened, non-sticky compound is easy to handle during transportation and at the molding press. Hydroxides and oxides of calcium and magnesium are the most commonly used thickeners but isocyanates are occasionally used instead of, or together with, them. The thickeners are normally dispersed in a non-thickening carrier resin before they are added to the compound. Acrylic, styrene and non-thickening saturated polyester resins are used for this purpose.

Figure 2. One-inch chopped glass fibers.

2.1.5 Initiators Polymerization is initiated by adding organic peroxides to polyester resins. As molding is usually at 240 to 340 °F, it requires high temperature initiators such as t-butyl perbenzoate. Mixtures with lower temperature initiators such as t-butyl peroctoate are frequently used to speed cure.

2.1.6 Internal Mold Release Zinc stearate, at proper levels, is almost universally used because it is effective and does not interfere with subsequent paint and bond adhesion operations. Good dispersion is critical and care must be taken to avoid foaming during mixing. Calcium stearate is used in higher temperature molding compounds.

2.1.7 Pigments and Colorants SMC's can be pigmented to achieve the desired shade. However, success with one color or pigment in a given SMC does not guarantee success with another. The pigments must be matched for each SMC formulation. SMC surface can also be textured by proper treatment of the mold surface.

2.2 SMC Production

SMC machines come in different sizes and volumes. Typical laboratory units make 24″ wide sheet while most production-size machines are 48″ wide, capable of producing in excess of 50 million pounds of SMC per year. This section emphasizes the steps in the production process rather than the machinery used.

2.2.1 Incoming Quality Control Incoming quality control of raw materials used in SMC include the typical property testing expected of the raw materials: percent solids, viscosity, moisture, particle size, molecular weight distribution, etc. However, these tests are not adequate to always predict the performance of the materials, and, hence, most molders also specify "use" tests such as formulation thickening tests to help decide the acceptability of the raw materials or to assist in processing these materials.

2.2.2 Batch vs. In-line Mixing In batch mixing, all the ingredients are combined together in one mix tank and then processed through the SMC machine. By having multiple tanks, this batching process can be run without stopping the SMC machine. However, to avoid premature thickening, it is more common to omit thickener during batching and, instead, add it to the feed stream at the SMC machine.

Thus, the in-line mixing process has at least two streams. The "A" stream contains the unsaturated polyester, the low profile additive and most of the other ingredients while the "B" stream contains a saturated polyester and the maturation agent, usually an alkaline earth oxide such as calcium oxide. Additional streams can be used to introduce other ingredients such as pigment concentrate or a second maturation agent. The streams of materials are mixed in-line by use of either static or dynamic mixers. The semi-continuous process is generally used when large quantities of the same formulations are run. The ratio of A side to B side typically ranges from 10:1 to 30:1.

2.2.3 Mixing Procedure Current mixing practices include using either high shear or low shear mixers to mix the SMC paste, which is a mixture of resin and LPA, filler and other ingredients as shown in table 1. Generally, all the liquids are added first, then minor solids and finally the filler. The paste generally heats to 90 °F during mixing, which reduces the viscosity and speeds the initial maturation reaction. Low shear mixing under vacuum is also practiced.

2.2.4 SMC Machine It is at the SMC machine, as shown in figure 3, where the paste and the reinforcing fibers come together and form the sheet. The basic parts of the SMC machine are the doctor boxes, where the paste is spread onto a carrier film; the chopper, where the fibers are chopped; the bed, where the chopped fibers fall and where continuous fibers or cloth can be introduced; the compaction unit, where the paste and the fibers are squeezed together to wet the fiber with the paste; and the take-off area, where the SMC is either put on rolls or placed into boxes. While the production SMC machines are capable of processing continuous fiber reinforcements, in practice, most class-A SMC's contain only chopped fiber reinforcement.

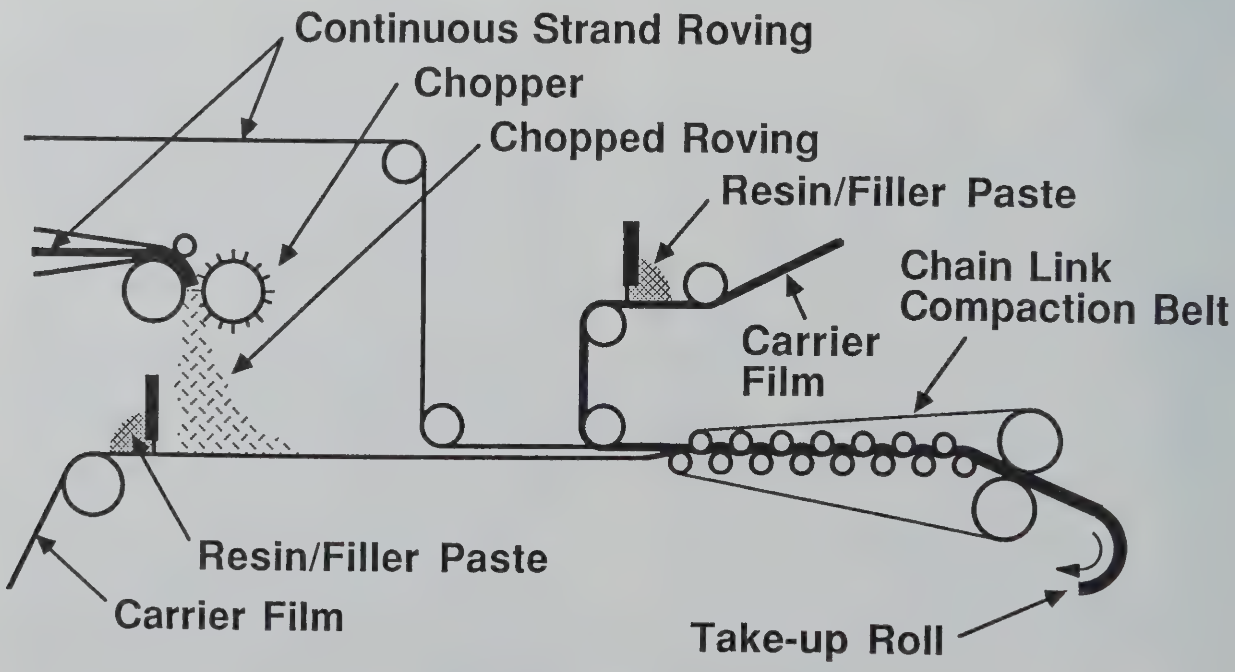

Figure 3. SMC machine schematic.

2.2.5 Handling of Compound The SMC sheet is either rolled up or festooned into boxes. The rolling process has been slow, the rolls take up more space in storage, and frequent changes are required at the press. The festoon method leaves folds in the sheet where the material folds in the boxes in the filling process.

2.3 Maturation

Maturation is the process where the sheet develops viscosity to allow it to carry glass fiber during molding and to become tackfree and handleable. Paste viscosity delivered to the SMC machine ranges from 10,000 to 40,000 cPs. After a day to a week of storage, paste viscosity rises to the moldable 10 to 100 million cPs range. The maturation rooms are temperature controlled for predictable viscosity build and to avoid premature gelling.

Several methods of maturation are used in the SMC industry. The most popular is the use of metallic oxides. The next most widely used method is isocynate maturation, which offers the promise of fast and predictable viscosity builds.Isocynates can be used in conjunction with metallic oxides in dual maturation systems. In practice, isocynates have proved to be difficult to control and, when used alone, yield gel particles.

2.4 Molding Process

The compression molding process has several steps that must be considered when converting the SMC charge into a final component. Each of these steps has its own associated challenges that must be overcome to ensure a successful molding operation. These steps, the issues to be addressed, and the opportunities for innovation are discussed below.

2.4.1 Charge Pattern Development The pattern and placement of the SMC charge in the mold is one of the most critical process parameters in SMC molding and yet one of the least understood. Most molders depend on the experience of their process engineers. Typically, charge patterns cover anywhere from 20% to 90% of the mold surface. Without vacuum assisted molding, most Class-A panel charge patterns cover less than 35% of the mold surface. The main concerns in charge pattern development are surface appearance, minimizing porosity and blisters, filling the part uniformly, and avoiding knit lines or at least putting knit lines in non-critical areas.

2.4.2 Mold Flow Several models have recently been developed for flow of SMC inside a mold. These models are useful in helping to develop charge patterns and processing conditions. They use an approximate material rheology and are based on parallel closure of the platens. Improved models are needed to more accurately predict flow, charge placement, and charge pattern.

2.4.3 Fiber Orientation and Distribution Much work has been done on fiber orientation and distribution. As the SMC flows in the mold, the glass fibers tend to become oriented in the direction of converging flow and perpendicular to diverging flow direction. Fiber orientation and distribution affect mechanical properties and part dimensions.

2.4.4 Charge Preparation Typically, SMC charges are prepared manually or with the assistance of mechanical devices. The charges are cut and stacked to assist the operator in loading the press to the specified charge pattern. In most charge patterns, there are areas where the charge is more than one ply of SMC thick. The charge shape often crudely resembles the part and encircles window and other large cutout areas so as to avoid knit lines that would otherwise form. Care must be taken not to trap air between the plies of material. In some cases, charge preparation may include preheating and compacting the material by various methods for faster cycles and improved quality.

2.4.5 Charge Placement The placement of the charge is very critical to the molding process, particularly when older presses are used. A charge misplaced by as little as 1 inch on a 36 sq. ft. part can lead to an unacceptable part by moving a knit line or result in a part not completely filled. Charges giving incomplete fill are often used to reveal the flow pattern and help in choosing a shape and placement that avoids defects.

2.4.6 Velocity Profiling Velocity profiling refers to the speed of the press closure. Older equipment generally has three press velocity settings. The fastest speed is used to bring the press down to just above the material surface. The intermediate velocity is used to start the flow and the slow speed is used to complete mold filling. Typical pressing speeds are around 0.1 inch per second (ips), but very large parts may offer too much resistance to reach this speed. Newer presses have many more velocity settings which allow the process engineer to program the rate of closure to better control the speed at which the material is flowing.

2.4.7 Pressure Profiling Pressure profiling refers to the pressures used during the compression and curing cycle. Newer presses allow the process engineer to modify the pressure exerted on the panel throughout the closing and curing cycles. Pressure profiling is primarily used to enhance the appearance of panels but may affect the physical properties of the part as well, most notably, water absorption. The pressure used averages 1000 psi, with higher pressures needed for deep draft parts and lower pressures used during cure to improve low profile action.

2.4.8 Molding Temperature Typical molding temperature for SMC is 300±10 °F; however, a much wider range, 240 to 340 °F, can be used with cure rates doubling every 20 to 30 °F for a typical recipe. The temperature difference between the two mold cavities is generally kept small. Too great a temperature difference can cause one mold half to expand or shrink against the other and can damage a mold by causing the shears to engage and, thus, lock the mold together.

2.4.9 In-Mold Coating (Liquid & Powder) Liquid in-mold coating (IMC) is a process in which the curing cycle of the SMC is interrupted very near or after its completion, and a liquid resin is injected onto the surface and cured under heat and pressure.

Liquid in-mold coating was developed in the United States in the mid-1970's through joint efforts between General Tire (now GenCorp) and General Motors. The purpose of in-mold coating was to seal surface porosity in the molded SMC and to act as a coat of primer to enhance finished appearance. Liquid in-mold coating is widely used for Class-A panels which are supplied to U.S. auto manufacturers. In-mold coatings are one-component conductive materials that cure in 30 to 60 seconds at 300 °F for thicknesses of 0.001 to 0.006 inches.

In the powder in-mold coating process, powder is applied to the mold surface at the start of the molding cycle. The powder coating is partially cured before the pressing of the SMC begins, completes cure during the molding cycle, and is bonded to the panel when it is removed from the tool. Powder coating is used primarily for non-automotive applications, in particular, sanitary ware. Such coatings are typically 0.004 to 0.008 inches thick, abrasion resistant, and rougher than the liquid coatings.

2.4.10 Part Removal For a typical molding, the part will be on the core half of the mold when the press opens. The first step in part removal is to lift the part away from the mold. This lifting is usually accomplished through either ejector pins built into the mold that lift the part off the mold or, less frequently, by blowing air underneath the parts to lift the parts off the mold. Once the part is off the mold surface, it can be removed manually or mechanically to a cooling fixture or a deflash station.

2.4.11 Deflashing In compression molding, some of the SMC is forced through the shear edge of the molds and cures to become flash, which needs to be removed from the part. Flash is typically 0.002 to 0.005 inches thick; however, on tools with badly fit or worn shear edges the flash can get much thicker. The traditional way to deflash a part has been to sand the edge back or use a combination of knife trimming and sanding. This method works well on parts with minimal flash.

Recently, robots equipped with sanders, high speed routers, or water jets have been used to deflash parts.

2.4.12 Trimming In compression molding, it is common practice to mold in areas of the part, such as attachment holes or headlight openings, at reduced thickness rather than flow around them so as to avoid knit lines. These areas which are referred to as mash out areas, need to be trimmed out. Stamping them out is most common but routing, drilling, and water jet cutting are becoming more widely used to give better cuts.

2.4.13 Part Handling A typical handling sequence starts with the part to be transferred from the mold to the deflash station, to a trimming station, to a bonding station, to the finishing and/or prime line and, finally, to packaging before shipment to the customer.

2.4.14 Assembly and Bonding Although a major advantage of compression molded SMC over steel is consolidation of parts, most molded parts require some assembly or bonding. Assembly can be accomplished with traditional mechanical fastening, such as riveting or bolting, or with adhesive bonding. The adhesives most commonly used are urethanes and epoxies. Bonding has received much attention recently. The adhesives have been formulated to be primerless and to cure faster with the traditional method of conduction heat transfer. New methods of energy transfer to cure the adhesive have been adopted in production, including hot air impingement and radio frequency heating. Currently, large assemblies are being bonded in cycle times of less than 60 seconds, whereas in 1984 these same parts would have required more than 180 seconds.

2.4.15 Finishing Finishing of the molded or assembled part can be divided into the following areas: inspection, repair, priming, and topcoating.

Inspection: Inspection is still highly labor intensive. Detecting and measuring surface defects such as microcracking, waviness and bond line readout have been difficult to automate. Although considerable advances have been made in this area, there is a need for an accepted standard method to measure surface defects.

Repair: Repairing parts requiring Class-A appearance is limited to sanding out scratches in the IMC coated surface and filling pits and porosity with a polyester compound on the uncoated surface. There is no satisfactory method to repair fractures, blisters, or waviness in Class-A parts. Thus, a world-class molder takes a disciplined approach to producing a porosity-free, Class-A surface from the mold and maintains that surface during handling.

Priming: After washing, priming is currently performed by spraying paint over the surface manually or robotically. This can be done electrostatically if parts have IMC, since it is conductive.

Topcoating: The typical top coat consists of applying a base coat of color paint, typically less than 0.001 inches thick, to the primed surface, followed with a layer of clear coat paint, typically 0.0015 inches thick and a bake at 275 to 300 °F.

2.4.1 Packaging/Shipping Packaging and shipping of parts constitute a major cost in the manufacture of Class-A compression molded assemblies. While structural parts can be nested against each other, the Class-A assemblies must be packaged for shipment to avoid damaging the surface. Shipping containers must also be designed to prevent stressing the parts, in ways they were not designed for, during transportation by rail or truck.

3. Applications

The premier application of Class-A SMC body panels is the Chevrolet Corvette (see fig. 4), with an annual volume of 20,000 to 30,000. This vehicle's body and underbody panels have been made of composites since its introduction in 1953. The most recent application is the General Motors APV mini-van, with a projected volume of 225,000 units per year. What makes SMC composites attractive in such volume ranges can be summarized as follows:

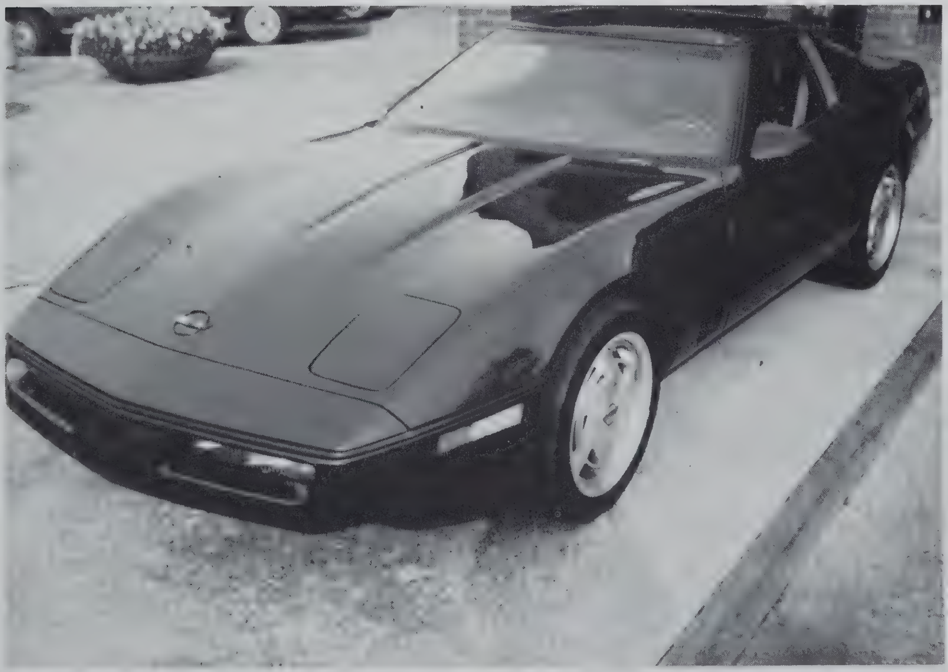

Figure 4. The premiere application of Class-A compression molded body panels: the Corvette.

3.1 Part Consolidation

Parts made of several sheet metal components can often be consolidated into one composite part, thus saving assembly plant costs for labor, floor space, handling and storage. In a typical grille opening panel, 30 metal pieces are consolidated into one piece. Tooling costs for SMC are 20% to 30% of steel stamping, since there are fewer types of parts and molds to make and presses are significantly lower in cost for annual volumes of less than 250,000 units.

3.2 Light Weight

Typical SMC panels are approximately 30% lighter than a steel counterpart. With the use of ultra-light fillers such as glass bubbles, this weight reduction can be enhanced to about 50%. The latter components are currently used as the reinforcing member of the Corvette body panels. Work is in progress to apply this technology to SMC outer skins.

3.3 Design Flexibility

Designers have a large menu of physical and mechanical properties to choose from. These properties can be tailored in any direction and for any functional requirement. Shapes can be complex and vary in profile so long as there is a small positive draft to ease removal of the part from the mold.

3.4 Material Flexibility

Compounds with a wide variety of properties can be made to meet all performance requirements. The amount and type of reinforcement can be varied to meet directional and special structural criteria. The strength-to-weight ratio of SMC composites surpasses that of steel and other conventional materials. SMC composites offer dimensional stability unmatched by most competing plastics. The heat distortion capability of SMC composites is greater than 400 °F, and the thermal expansion matches steel, allowing it to be used in combination with steel parts.

3.5 Corrosion Resistance

This is an inherent property of all composites and, of course, SMC is no exception. They do not rust or corrode and are resistant to most chemicals.

4. Future Opportunities

Although significant strides have been made in perfecting the compounding and in mechanizing the molding of SMC, the whole process is still more of an art than science. Perhaps this is partially due to the large number of ingredients used and the increasing number of raw materials and equipment suppliers. While this enhanced competition has improved the economics, it also has increased the number of potential compounds. Fortunately, the "art" of compounding and molding comes to the rescue and allows the molders to use different materials and compounds in similar applications with remarkable success. An overall objective in seeking future opportunities, thus, would be to better characterize and quantify the compounding and molding operations so as to increase consistency, quality and reproducibility of the molded parts.

4.1 Molding

One of the major challenges to compression molding of SMC is to completely eliminate porosity. The current state of the art requires either IMC to seal the surface porosity or a combination of vacuum molding with two prime and bake cycles. Neither of these approaches completely eliminates surface porosity, and both add considerable cost to the product.

Surface waviness is another area where improvement is required. Although molded SMC panels have surfaces comparable to many steel panels, the best SMC panels are still not better than the best steel panels. If a process/material can be developed to provide improved surface over steel, the use of SMC to replace steel panels will greatly accelerate.

It is a challenge to obtain part-to-part consistency for structural load-bearing applications and to monitor it through inline non-destructive testing. Currently there are many variables which affect the consistency of structural parts: mix consistency, mix placement, processing conditions, SMC flow, and fiber orientation and distribution. It is very desirable to inexpensively and nondestructively test these parts to ensure that knit lines or improper fiber orientation that could lead to premature failure are not located in critical areas.

4.2 IMC

One area for future development is to reduce the total cycle time needed for high-speed production to less than a minute. This means that the IMC must cure in 15 seconds or less without sacrificing any other attribute. Furthermore, improvement in first-run capability where no finishing is required on the coated panels is essential. Specifically, improvement in the surface appearance of the coated part and a reduction in the required IMC film thickness for better economics should be considered. Perhaps even more desirable would be to formulate SMC's that do not require surface coatings to begin with and can directly be primed for painting.

4.3 Charge Loading and Unloading

Placement of charge and removal of the molded part must be gentle, more reliable, and faster—e.g., a total of 10 seconds or less. Complex charges may have to be sewn or otherwise joined before loading to enable this. Unloading "boards" densely covered with suction cups or with forks so as to fit between ejection pins is the current thinking.

4.4 Part Removal

An area for future development is ejecting the part from the mold surface. A problem with ejector pins is that typically those pins at the surface will leave marks on in-mold coated Class-A surfaces. These defects are raised areas that require sanding. Improved design to remove parts without surface damage or warping which causes cracking is needed.

4.5 Deflashing

An area for additional development is in shear technology: to be able to better fit and maintain shear to minimize flash, and high-speed economic methods to remove the flash. Deflashing could be combined with the trimming operation to save in equipment and time.

4.6 Trimming

A problem associated with all methods of part trimming is the tendency of the trimmed edge to outgas during painting, which results in a paint pop. A second problem associated with trimming and drilling of openings is the current inability to produce edges with no fibers or "fuzz" in the opening. Water jet cutting and drilling could give the quality but is too slow and costly. Laser cutting, while not very successful so far, has the potential to become a viable method for trimming and sealing the edges by fusing the matrix.

4.7 Part Handling

Handling parts which are typically 300 °F at the end of the cure cycle can be a difficult task, especially with large, complex shapes. Molded panels have lower stiffness until assembled and are easily scratched if handled improperly. In a fast cycle process, about 8 to 10 seconds are allocated for charge placement and part removal. This calls for state-of-the-art robotic, or other ingenious methods of, part handling. One may consider a template, tray, or carrier frame which stays with the part through secondary operations.

4.8 Assembly and Bonding

The challenge here is to develop alternative forms of part assembly which do not require bolts, rivets or adhesives! Although adhesive bonding cycle times have been reduced, there is still the cost associated with the adhesive material and the bonding fixtures and robots to dispense the adhesive. Faster cycles, faster and more accurate laydown, thinner layers, and cheaper non-dedicated fixturing need to be developed.

4.9 Finishing

Inspection: The challenge is to develop a method to measure quantitatively, rapidly—i.e., on-line and automatically—surface defects for inspection. Ashland's LORIA and Diffracto D-Sight units are good for off-line but are slow and time consuming.

Repair: A less labor-intensive repair method for scratches, pits, and porosity is desirable.

Priming: The goal is to develop a primer that does not require the significant capital cost associated with the current practice of power wash and painting, the long bake ovens and air emission/water effluents concerns, and will not release VOC's into the atmosphere. Powder coating after molding to replace both IMC and priming, as well as in-mold coating that eliminates priming, should be considered. The coating *must* hide read-outs completely.

Topcoating: The same problems with capital and VOC emissions described above need to be overcome in topcoating. In addition, topcoats, especially the new high-glamour type, have very poor hiding capacity, and ribs and bosses or bonded inner panels will read through on the surface of the parts. The challenge is to have the glamour paints without the read-through. Low-temperature paints, film paints or other novel approaches need to be explored.

4.10 Packaging/Shipping

New methods of packaging to allow for more parts to be shipped per space, rail car or truck, while preventing any damage to the parts are very desirable. Shrink wrap is used sometimes.

4.11 Incoming Quality Control

A significant area for innovation is to develop meaningful tests that better characterize the raw materials in order to eliminate the need for "use" type tests. For example, a test is needed to measure an as-molded panel's ability to resist fracture as it is removed from the mold. Development of a test that correlates the raw materials' properties to fracture resistance of the panel at molding temperatures would be very desirable.

4.12 Batch vs. Semi-Continuous

A challenge for future development is for continuous mix operation that removes the variability which can occur in batch and semibatch operations.

Ways to predict and provide feedback to continuously adjust the recipe so as to make a consistent product are needed, e.g., adjusting for water content variation in the resin to ensure a consistent maturation. Another opportunity would be speeding the mixing process, which can take 20 minutes for a 4000 lb. batch, improving the delivery of the raw materials to the tanks, and making the process more continuous.

4.13 SMC Machine

There are many areas that can be enhanced on the SMC machine, including the delivery of a uniform paste thickness to the carrier film and removal of the air trapped in the SMC. Another challenge is to improve the control of fiber laydown uniformity and orientation, also, edge waste/uniformity. Other areas include carrier film waste, feedback control to detect loss of glass roving feed, on-line monitoring of glass content and sheet weight and uniformity, higher speed and SMC thickness, ability to synchronously slow down the machine during start-ups and formulation changeovers to minimize waste.

4.14 Handling of Compound

An opportunity exists for improved handling of the sheet to allow for high-speed production without the problem of folds in the sheet.

4.15 Maturation

A challenge for future development is to develop materials, chemistry, and technology that permit maturation to be reached in a matter of minutes or hours upon completion of compounding. Furthermore, for the compound to remain stable, i.e., retain viscosity and texture for 2 to 4 weeks. The challenge is to obtain both the short maturation time and the long-term compound stability.

4.16 Flow Modeling

There are mathematical models that predict in-mold flow of SMC or IMC and offer guidelines for charge patterns and placement. However, these models are cumbersome to use and need refinement and ease of operation.

4.17 Mold Making

Improvements are needed in many areas: better transfer of design data to the tool maker's CNC machine; better quality metals for making the tools; better surface finish and means to measure same; better tolerances, fit, and dimensional accuracy; incorporation of heat management programs to properly locate heating lines or elements and feedback loops; better control and measure of surface temperature; development of uniform standards for tool quality and specifications; better delivery/quicker turn around time from tool shops, etc.

4.18 Design Aids

Sorely needed are better and more meaningful tests to measure the chemical/physical properties of SMC's, handbooks or design guides detailing such data, and easy-to-use design models to utilize the advantages of composites. Currently, very few parts are designed to take advantage of composites: flexibility of fiber orientation, placement, and mixed fibers. Instead, most parts are designed as sheet metal parts using the expected minimum properties throughout and then switched to composites.

Ideally, one would like to have the ability to tailor make SMC's to meet the desired performance requirements. An intelligent interactive computer program where one inputs the performance criteria and the program offers a menu of various material combinations, all of which meet those criteria but perhaps with different weights and economics, would offer the ultimate design flexibility.

4.19 Other

Other desired features include: thinner parts, ribbed Class-A, faster total cycle, no sanding, no IMC, and higher charge coverage to avoid knit lines, lower density Class-A SMC's, in-situ coating/priming, conductive SMC's to overcome EMI/RFI, self-reinforcing SMC's (upon exposure to elevated molding temperature), low molding pressure SMC's, SMC's with HDT of 500 °F to better withstand ELPO bake cycles, lower cost raw materials to enhance market penetration, and better documentation and presentation of composites energy management capability and crash worthiness. Recycling of SMC composite parts has received much attention lately. Both grinding and pyrolyzing SMC appear to be viable alternatives to landfill as the number of landfill sites decrease and their costs soar. Value-added end uses for ground SMC and pyrolysis solid byproducts are actively sought by industry members.

5. Summary

As discussed throughout this section on compression molding, although great strides have been made, additional refinement and imagination could lead to exciting innovations. The compression molding process has evolved into its current position for automotive applications and continues to evolve at a rapid pace. Perhaps the most desirable innovation would be the development of SMC's with improved surface quality and economics in order to more effectively compete with steel. Other improvements would include faster curing SMC's and elimination of priming at the molders' facility. Educating the automotive designers to design in composites is perhaps the next most important step in promoting the use of SMC's. This information is not intended to be all encompassing of everything that is known on this subject but to provide a basis from which a reasonable understanding of the process and its intricacies can be gathered and applied. The reader is encouraged to seek additional details in the literature in the areas of specific interest.

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Technological Opportunities in Thermoplastic Composites Injection Molding Manufacturing Technologies

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The historical development of the injection molding process, an overview of the variety of thermoplastic composites available today, a listing of important markets and typical applications in those markets will be presented. An analysis of several significant problem areas associated with injection molding and their effects will also be examined.

Technological opportunities in materials, process, engineering, mold design, finishing and education will be specifically examined for the items listed. Each of these individual items will be treated in some depth to acquaint the reader with the state of the art, associated problems and technological opportunities.

Key words: anisotropy; aramid fiber; barrel design; carbon fiber; co-injection molding; computer aided engineering; differential cooling; dimensional stability; electromagnetic interference; electrostatically dissipative composites; fusible core injection molding; glass fiber; hollow gas injection molding; injection molding; interpenetrating polymer network; liquid crystal polymers; mold design; multiple line injection feed; orientation effects; push-pull molding; reactive processing; screw design; surface finish; weld line.

1. Historical Perspective

The injection molding process goes back to a patent issued to John and Isiah Hyatt in 1872 for a machine designed to mold camphor-plasticized cellulose nitrate (celluloid). The first multi-cavity mold was introduced by John Hyatt in 1878.

The modern injection machine consists of a clamping portion that contains the mold and the injection end, which feeds, melts and meters the plastic material. The injection portion of the machine has evolved over the years from a single-stage plunger to a two-stage plunger-pot to a two-stage screw-pot to the reciprocating in-line screw machines in common use today.

The reciprocating in-line screw injection molding machine (see fig. 1) accepts solid plastic pellets from the feed hopper. These pellets contact the barrel to form a thin film of melted plastic on the barrel surface. The relative motion of the barrel and screw conveys the melt forward as a function of the difference in coefficients of friction between the plastic and the barrel wall and the plastic and the screw. The leading edge of the advancing flights of the screw pick up the molten plastic material, forming a circulating pool of material ahead of the screw flights. The screw acts as a plunger injecting the plasticized material through the nozzle into the mold where the plastic is held under pressure until it has cooled sufficiently to be ejected.

2. Materials, Markets, and Applications

Injection moldable thermoplastics can be hard or elastic, rubbery or tough, crystal-clear or opaque as well as strong, weather-resistant, electrically-

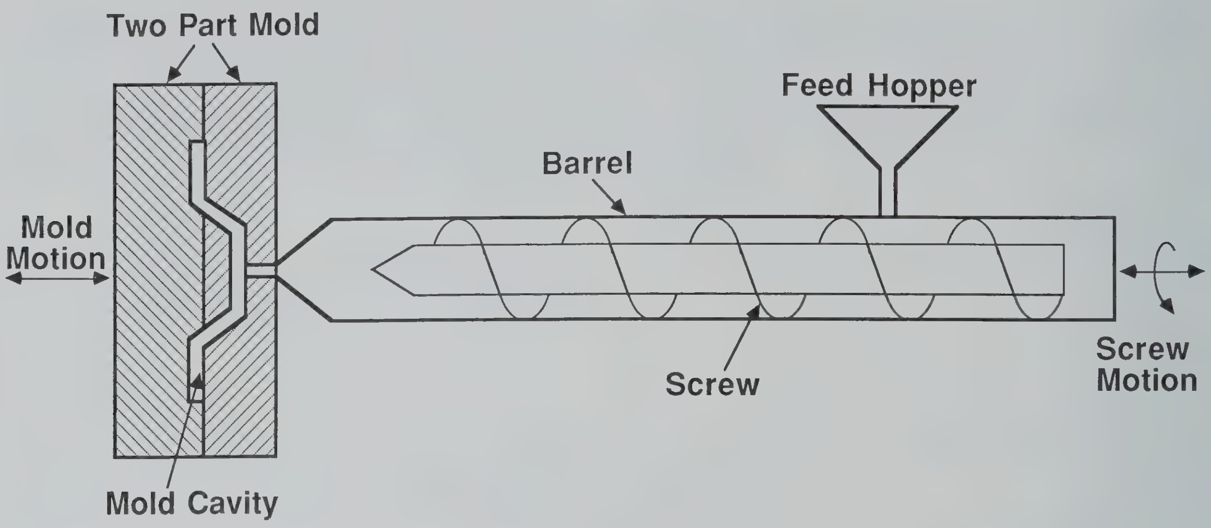

Figure 1. Injection molding schematic.

conductive, wear-resistant, EMI-attenuating, flame-retardant, heat-stabilized, magnetizable and they are available in a vast variety of closely matched colors.

Injection molded parts of thermoplastic composites are used in the container, automotive, furniture, appliance, marine, aerospace, consumer, leisure, sporting goods, industrial, business machine, electrical, construction, electronic, agricultural, telecommunications, and household market segments in applications as diverse as IC chip carriers, fuel pump impellers, chair handles, timer bodies, boat propellers, high temperature connectors, camera housings, drumsticks, tennis racquets, compressor vanes, keyboard frames, switch boxes, water meter housings, molded printed circuit boards, pesticide dispersing pumps, housings, switches and connectors, and mop wringer body and gears, respectively.

3. Problem Areas

Several major problem areas (in order of priority) associated with the injection process can be identified:

1. Dimensional stability of the molded part
2. Weld line integrity of the molded part
3. Molded part surface finish
4. Differential cooling effects
5. Anisotropic properties of filled and reinforced materials.

Each of these is discussed below.

3.1 Dimensional Stability

Generally, very few injection molded parts can be held to extremely close tolerances, i.e., less than one one-thousandth of an inch. Tolerances that can be met in production are generally 5% for parts 0.020″ thick, 1% for parts 0.5″ thick, 0.5% for parts 1.0″ thick, and 0.25% for parts 5.0″ thick. Since the injection molding process is a relatively high-volume, low-cost process, usually utilizing multi-cavity tooling or family tooling, achieving the desired dimensional accuracy in a molding is often a constant struggle that involves controling the degree of repeatability-in-performance for the machine/mold/material/part design/cycle time.

3.2 Weld Line Integrity

Weld lines can develop during molding with improper design of the part, poor molding techniques, or very highly oriented, very anisotropic materials such as liquid crystal polymers or fiber reinforced composites. Weld lines can lead to severe reductions in mechanical properties when the two “flow fronts” do not knit together well. There is also an aspect of displeasing aesthetics created by the weld lines.

3.3 Surface Finish

The ability to develop a high gloss, low roughness surface on a molded part is important for the leisure, consumer, appliance, sporting goods, furniture, household and automotive industries. Quite often, a secondary operation such as electroplating, vacuum-metallizing, decorating, bonding, painting or joining is affected by the surface finish of the part. The choice of matrix resin and reinforcement, mold surface finish, mold temperature, injection speed and pressure can affect the ultimate molded surface finish.

3.4 Differential Cooling Effects

Parts injection molded from thermoplastics are smaller than the cavity in which they are molded. The reason for the difference in size between the cavity and the part is that the cavity is filled with a melt at high temperature that has a lower density than the cooled, solid plastic. The difference between *volume* of the mold and volume of the part is termed the mold shrinkage. Traditionally, however, the difference between any *linear* dimension of the cavity and the corresponding linear dimension of the part is called the mold shrinkage of the plastic. The changes in density of a plastic during molding (actually, specific volume) depend largely on temperature of, and pressure on, the melt. As melt temperature increases, specific volume increases, and as pressure increases, specific volume decreases. In practice, then, final mold shrinkage is determined by the temperature and pressure of the melt in the cavity at the time of gate seal-off and the thickness and crystallinity of the frozen skin. Since the specific volume of a solid material is considerably less than that of any melt, the greater the thickness of the solid layer, the smaller the size change as the part comes to room temperature. Minimum shrinkage is obtained when that part is completely solidified when the gate freezes.

Nucleation raises the temperature at which solidification occurs and thereby hastens freezing of both the part and the gate. The usual effect of nucleation is to reduce mold shrinkage, but it also increases the amount of frozen-in flow orientation, which can lead to non-uniform shrinkage in flow and transverse directions and, occasionally, part warpage. (The transverse shrinkage will be greater.)

Part and mold geometry are also very important in determining mold shrinkage. If the cavity contains undercuts or cores that restrain the free shrinkage of the part, the as-molded shrinkage will be less than for an unrestrained part. The post-molding or aging shrinkage, however, will be greater for a part that is restrained from free shrinkage in the mold because of greater strain within the part.

Varying wall thicknesses from thick to thin sections in a part can lead to the formation of sink marks. Since the parts in a mold solidify from the outer surfaces toward the center, sinking of the surface will occur in the thick section. Thick sections should be cored, properly radiused, hollow gas injection molded or the cycle increased to avoid sinking.

3.5 Anisotropic Properties

The addition of flakes or fiber with an aspect ratio to a resin matrix usually results in molded parts with varying degrees of anisotropic properties due to orientation effects. The orientation effects generally result in fiber or flake preferentially aligned in the flow direction. The outside "skin" of the molding is also generally more anisotropic than the "core" region. Obviously, proper part design, tool design and material selection can minimize these effects. Curiously, the shorter the fibers, the greater the anisotropy!

4. Business Areas

The reinforced thermoplastic composites (RTP) industry has been enjoying an 8–10% compounded growth rate for the last 10 years. The major markets are in automotive which consumes roughly half of the RTP industry production and the electrical and business machine industries. The combination of stiffness, strength, chemical resistance, flame retardancy, elevated temperature dimensional stability and close tolerance molding make the RTP composites especially suitable for many applications.

4.1 Materials

The processing of high-temperature reinforced thermoplastics such as PSO (Polysulfone), PPS (Polyphenylene Sulphide), PES (Polyether Sulfone), PEEK (Polyetheretherketone), PEI (Polyetherimide), PEK (Polyetherketone), and LCP's (Liquid Crystal Polymers) offers opportunities for those processors with the materials handling expertise, dryers, and oil heaters to properly process these materials.

Processors with the ability to properly mold the newly introduced pultruded, long fiber, reinforced thermoplastic composites will be in an enviable position if they can successfully maintain fiber length, control fiber orientation and understand skin core morphological phenomena.

An opportunity exists for processors who understand the language of tribology and organize to produce molded parts to rigid specifications for wear factor, coefficient of friction, limiting-pressure-velocity and surface finish.

Electrostatically dissipative (ESD) composites, include a variety of fibers or reinforcements (carbon black, metal flakes, metal fibers, carbon fibers, metallized carbon fibers). The ESD processor who can marry the intricacies of electrical engineering terms and test methods (electrostatic conductivity, electrically dissipative, conductive, triboelectric effects, surface resistivity, volume resistivity, etc.) and offer on-site electrical test capabilities coupled with unique processing capabilities can become established quickly as a specialty house in this market.

Fiber-reinforced thermoplastic composites offer a serious challenge to the processor interested in dimensional control and tolerancing because of fiber orientation which leads to differential shrinkage and consequent warpage in composites with semi-crystalline matrices. However, in fiber-reinforced amorphous matrices, extreme tolerancing can be achieved with proper processing. The fiber-reinforced semi-crystalline resins do, however, usually offer improved tolerancing capability when compared to the neat semi-crystalline resin. An understanding of AGMA (American Gear Manufacturers' Association) gear tolerance limits and the techniques required to achieve the requisite "tooth-to-tooth" or "total indicated runout" (TIR) tolerances in molded plastic gears can be invaluable in developing a specialty business in this area.

The processing of carbon fiber-reinforced thermoplastics involves a rapid growth area requiring molding machines equipped with "flow-through" nozzles to attenuate fiber attrition and "electrically-hardened" control panels and work areas to avoid shorting out of electrical equipment with stray carbon fibers.

The aramid fiber-reinforced materials present a challenge and a dilemma to the processor. Successful applications to date involve long-fiber pultruded aramid fiber-reinforced materials that are subsequently extruded into shapes or structures. This processing scheme avoids the high shear extrusion compounding and injection molding steps which lead to severe fiber damage to the outer skin of the aramid fibril bundles and result in greatly decreased mechanical properties. Obviously, an injection molding process that minimizes aramid fiber damage employing long fiber pultruded composites would be of great benefit.

A series of recent patents highlights the capabilities of interpenetrating polymer network (IPN) modified reinforced thermoplastic composites to achieve dimensional stability in molded gears and other molded parts requiring exceptional shot-to-shot reproducibility. This technology has been reduced to practice only at major OEM's and has not been advanced or well understood at the molder level.

The development of filled or reinforced thermoplastic composites suitable for electromagnetic interference (EMI) attenuation has been fraught with difficulty. The successful EMI attenuating thermoplastic composite should offer good attenuation across a broad frequency range, good surface appearance, colorability, good mechanical properties and low cost. To date, no composite developed to attenuate EMI has met these requirements. Preferential orientation of conductive flakes or fibers, control of skin/core morphology, or co-injection of a conductive skin layer and foamed core or an aesthetic skin layer and conductive core could also be the answer.

Injection moldable magnetizable thermoplastic composites were introduced in 1969 and have enjoyed little growth in over 20 years because of the limited number of injection molders in the United States (two) who understood the technology well enough to configure molding machines and tools to magnetize the molten melt during the molding cycle. The two successful U.S. molding enterprises just happen to be owned by electrical engineers who understand materials and molding.

The recent introduction of liquid crystal polymers (LCP's) has presented the processor with a unique set of opportunities and problems. The LCP's offer an extremely low viscosity melt, making them an ideal high-temperature material for electronic encapsulation. However, the high degree of orientation experienced with LCP's leads to severe weld line problems that must be addressed. The use of the new Klockner Desma "push-pull" molding technique or the "multiple live injection feed" (see figs. 2 and 3) molding technique developed at Brunel University in the United Kingdom might solve the weld line problems experienced with LCP's or the pultruded long fiber reinforced thermoplastics. Obviously the processor that establishes these new molding techniques in the United States will enjoy a pre-eminent position.

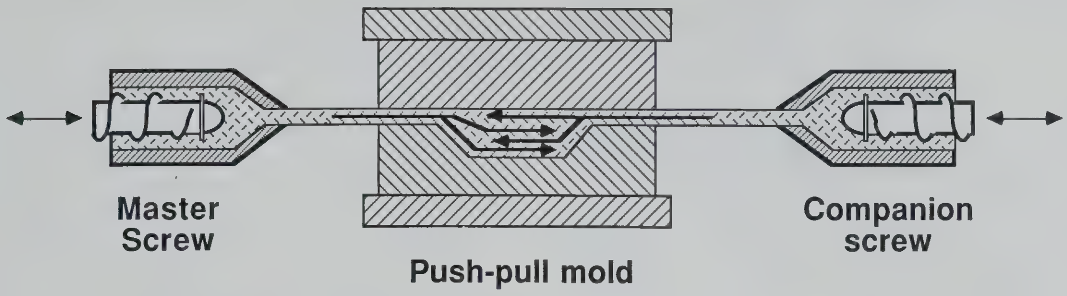

Figure 2. Principle of push-pull injection.

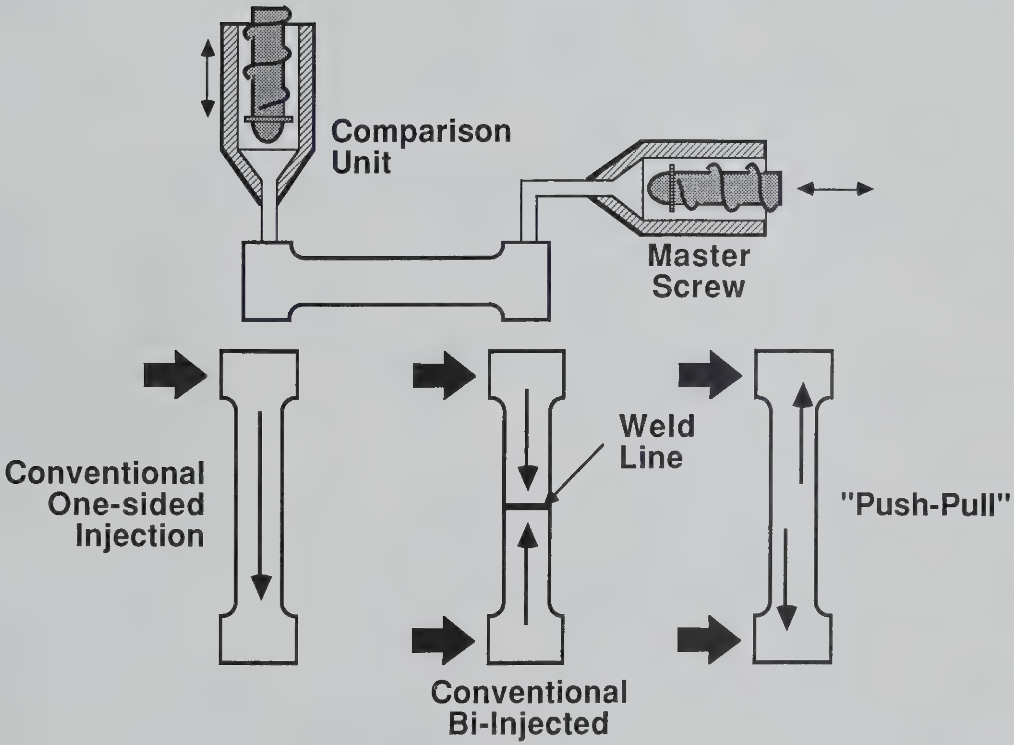

Figure 3. "Push-pull" LCP molding process.

4.2 Processing

An opportunity exists for a processor equipped with the capability to do reactive processing of reactively injected thermoplastic composites similar to ICI's RIMPLAST® products. The capability to inject liquid reactants or liquid/solid into a mixing section of the molding machine before transfer to the injection feed unit could lead to the development of unique IPN-modified, impact-modified, flame-retardant, or increased temperature resistance in thermoplastic composites.

The development of specific, unique screw designs, barrel designs, compounding sections, or venting sections in a molding machine would enhance the quality and productivity of thermoplastic composite injection molding over current practices. Many non-demanding applications could certainly be satisfied with a thermoplastic composite that was compounded, vented and injection molded in one processing step. Specific screw designs for crystalline or amorphous composites with the proper compression ratio, screw flight depth, and screw flight angle for the given composite being processed would also greatly enhance the chances for success.

A unique opportunity exists for processors to practice hollow gas injection molding in the United States under license from CINPRES LTD, U.K. or Detroit Plastics Molded (DPM). The hollow gas injection molding process (see figs. 4 and 5) requires

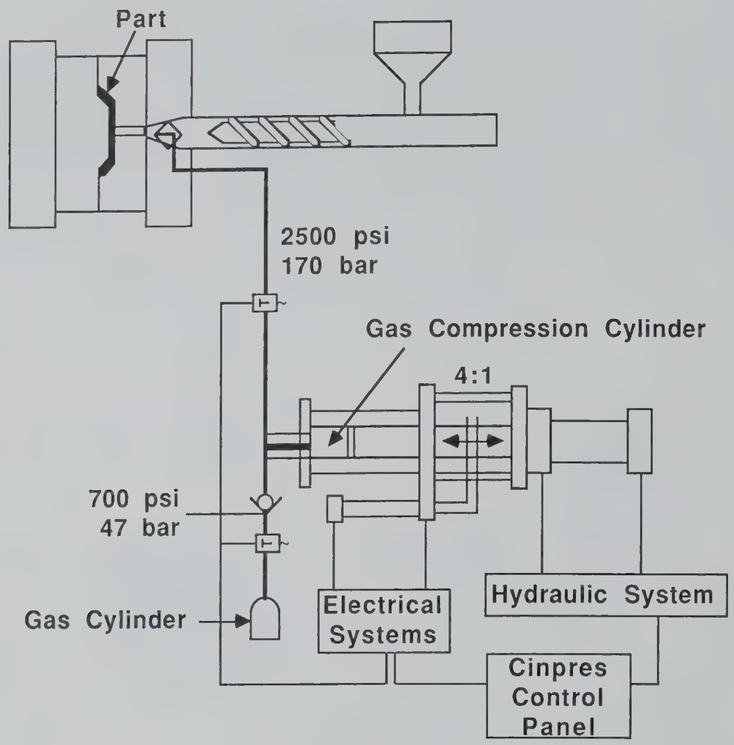

Figure 4. CINPRES® 1/gain process.

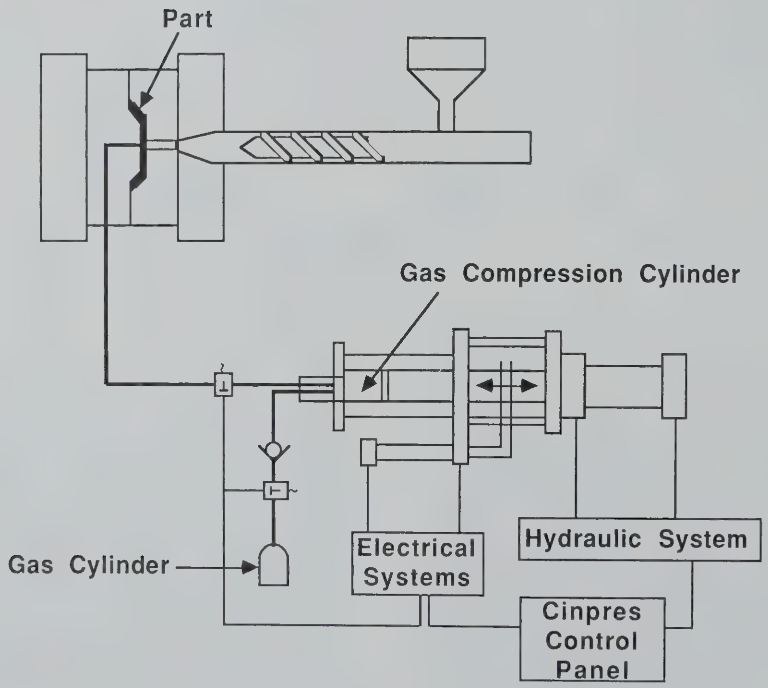

Figure 5. CINPRES® II process.

a separate gas (nitrogen) injection unit which must be hard-wired into the control panel of the molding machine to inject gas during the molding cycle. The process effectively allows for "hollowing-out" of the molded part by the injected gas, resulting in the elimination of sink marks, reduction in cycle time, reduction in part weight, excellent surface finish, and reduced shrinkage and warpage. At present, only a few molders in the United States are practicing this technology due to earlier patent litigation between CINPRES and DPM. The courts have now issued a ruling clearing the way for rapid future development of this process.

The fusible core injection molding process involves the casting of a low-temperature melting metal alloy core, over-molding the metal core with the specified reinforced thermoplastic composite, removing the metal core by induction heating and then recycling the core material to the metal melt tank. This process is employed for extremely complex shapes containing internal coring that cannot be satisfied with standard core pulls because of the cored length, geometry or curvature, and occasional die-block situations. The process can produce extremely complex shapes with large internal cored sections yielding a smooth inner surface. The Belland Corporation in Switzerland has recently introduced a soluble polymer core which is subsequently over-molded and then removed when treated with hot water. Disposal of the removed polymer core/water solution presents disposal problems. Electrovert/Fry offers equipment to produce the metallic cores.

Co-injection molding offers the capability to simultaneously inject two dissimilar materials from twin injectors as skin and core in the molded part. This allows for skins that are stiff, strong, flame-retardant, aesthetically pleasing, wear-resistant, conductive, EMI-attenuating, or hard, while the core could be molded as a foamed material or from a lower cost material. Battenfeld offers injection molding machines capable of co-injection.

A relatively new process termed "multi-live feed injection molding" has been developed at Brunel University in the United Kingdom and is presently being developed by Engel. The process allows injection through multiple gates equipped with separate injection units that provide oscillating pressure to produce greater alignment of fibers as solidification proceeds. The process also tends to produce molded parts with reduced weld lines, voids, cracks, or microporosities. A processor familiar with these techniques could certainly offer much needed expertise in the molding of liquid crystal polymers, pultruded long fiber composites, and ESD/EMI composites.

4.3 Part Design and Engineering

There is a need in the reinforced thermoplastic industry for a better and more widespread comprehension of the mechanical response of reinforced thermoplastics. This issue is fairly complex since the response is both nonlinear and anisotropic, and, more importantly, the typical mechanical response properties are not constant. For example, mechanical response will vary with temperature, load duration time, and strain rate (the three most important variables). For this reason, an extensive amount of data is required to fully understand just one material. However, the use of computers and powerful relational database software can change this. The computer could be used to take snap-shots of a material's response at specific temperatures, load duration times, and strain rates. These "snap-shots" can be achieved with interpolation and extrapolation routines. Such databases are required for the industry to fully understand the mechanical responses of reinforced materials.

Opportunities exist for anyone who can apply traditional mechanical engineering to the design of reinforced injection molded thermoplastic parts, while also understanding the injection molding process and material properties. Traditional mechanical engineering requires knowledge of problem definition, non-linear stress-strain response, anisotropic response, stiffness, metal replacement technology, static loads, intermittent loads, cyclic loads, impact loads, failure theories, and safety (to name some major subject areas). Like all design work, the manufacturing process must also be understood. For example, the limitations and consequences of injection molding must be considered at all times. Weld lines, residual stresses, gate locations, and draft are some important subject areas. Equally important, the engineer should have an understanding of the choices and limitations associated with reinforced materials.

Computers have become integral part of everyday life, but ascertaining when and how to use them to design an injection molded part is difficult because the injection-molding process is not precise. That is, there is always some guess-work involved in assessing the mechanical properties at any given location. Consequently, the output of a structural finite element analysis involves error over and above that associated with an FEA approximation. The injection molding process is also very difficult to model. For this reason, all filling analyses involve a fair amount of error. Computer-aided design is just as useful as in other industries, but a structural FEA and a filling analysis must be carefully reviewed before they are initiated. Few people understand the results, and, more importantly, few understand when the results are useful.

A lack of trained personnel, and consequently companies knowledgeable in the field of environmental technology, exists today for reinforced thermoplastic composites. Additional research is required to fully understand thermal and moisture expansion and how they relate to part design (e.g., tolerancing). Just as important is knowledge of how materials react and perform in different environments under stressed conditions. Designers today rely heavily on prototype testing in various environments, but in the future design engineers will demand more accurate data before initiating the design. For example, a stress-strain curve in a particular chemical environment and at a particular temperature would be enormously helpful to describe the expected decrease in strength from standard data sheet values. Environmental fatigue, creep, and impact data are also extremely useful. Thermoplastics are frequently chosen for chemical resistance, but quite often material behavior in a specific environment is not well understood.

4.4 Mold Design

Opportunities exist in design of injection molds for thermal management. Heat transfer (cooling and heating of cavity core inserts and plates) theory and specifically heat transport (cooling channel circuits) theory must be developed industry-wide for reinforced thermoplastic composites. Mold component manufacturing methods, preliminary mold layout, and design should be re-evaluated to give mold cooling system design a higher priority than ejection system design. Guided stripper plate ejection systems should be used to relieve mold cooling system design constraints. Circuit design must allow for turbulent coolant flow during mold operation. Innovative, small core component designs that rely on both coolant flow rate and metal thermal conductivity need to be developed. The advantages of well-developed mold cooling system designs must be demonstrated to end-users, mold builders, part designers, material suppliers and processors. Optimized cooling system design is worth the additional cost! Sufficient air gaps and hot runner manifold insulating stand-off pads are needed to minimize heat transfer from the manifold to the mold cavity or core. Separate cooling circuits are needed at the hot runner gate tip to control materials viscosity effectively.

Opportunities also exist in injection mold gate, runner system, and cavity layout design. A strong background in thermoplastic material shrinkage behavior, material rheology and heat transfer, injection mold design, and injection molding process control is essential.

The material shrinkage behavior must be known for long and short flow lengths, at various combinations of wall section thicknesses, and after flowing into mold cavities at different rates. New mold filling analyses and molded part shrinkage analysis software are helping to evaluate and verify shrinkage behavior. These variables are highly interactive. However, the development of shrinkage software which effectively predicts the properties of reinforced thermoplastic composites would be of benefit. The part geometry must also be evaluated to determine the optimum cavity orientation in the mold base. The cavity orientation must be selected based on optimum mold cooling system design requirements and part ejection system design requirements. The gate position and cooling system design must also be evaluated, with optimized design trade-offs made between the two. Uniform cavity filling is desired, and gate position is very important.

The pressure drop to fill a given mold cavity must not exceed the pressure available in the process control window of the molding machine. The melt temperature in the cavity must not drop too low during filling, or molded-in molecular strain will result. The number of gates and the length and diameter of runner systems are developed based on total shot volume and cavity geometry in the mold.

Molded part dimensional stability is controlled by the level of molded-in molecular strain in the part wall sections. Non-uniform cavity filling, packing, and cooling are the most significant contributors to part dimensional instability, shrinkage, tolerance, and warpage problems. Uniform cavity filling, packing, melt temperature, and cooling yield a uniform, dimensionally stable part.

4.5 Finishing

Specialization in bonding, joining, painting, welding, plating, decorating or assembling molded reinforced thermoplastic composites could offer some unique opportunities. The key to differentiation of the business would seem to lie in the development of unique processing equipment, tailored

tailored molding practices and/or unique finishing equipment adapted to reinforced thermoplastics.

4.6 Education

An opportunity exists for a small service company to offer expert advice on a consulting basis or through training courses in the areas of material selection, equipment selection, design assistance, and production assistance for reinforced thermoplastic composites.

4.7 Specialty Stock Shapes

A company able to produce stock shapes or thick-section slabs for specialty thermoplastic composites would satisfy a small but high-margin opportunity. These shapes or slabs would be purchased by OEM's to machine prototype specimens for testing prior to material approval in a given application.

The introduction of a standard line of reinforced thermoplastic composite gears for high-speed, high-load applications would allow OEM's to buy standard gears "off the shelf" for demanding applications.

4.8 Design Data Bases

Designers cannot readily access rheological and mechanical property information suitable for component design from current industry data bases of RTP's. An opportunity exists for development of an unbiased source of design and rheological data for RTP's suitable for applications engineering, end-use performance prediction and process development.

5. Summary

A large number of potentially attractive new business opportunities exist in the thermoplastic composites injection molding manufacturing technologies. These opportunities span the breadth of materials development, processing, tool design, applications engineering, computer aided engineering, data base generation and miscellaneous services.

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Pultrusion: An Expanding Technology

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Pultrusion technology is evolving at a rapid rate as a result of efforts and achievements by processors, material suppliers, universities, and research organizations. Pultrusion has become recognized by designers as a key manufacturing technology capable of providing reliable, cost-effective products with specifically tailored performance properties. The technology is evolving simultaneously on many fronts as the design community presents new challenges to processors eager to expand their markets. Their technologists are applying innovative processing methods to produce products which even 5 years earlier would have been considered outside the technical envelope. Suppliers which used to consist of primarily raw material firms seeking to sell resins, additives, and glass fibers now include companies in tangent industries offering manufacturing software, quality control instrumentation, machinery, and support services. Evidence of the new technical stature of pultrusion is seen in the dramatic increase in technical publications, funded academic programs, association sponsored seminars, and acquisition of processors by major corporations. All of this activity has brought considerable resources to focus on the needs and opportunities of the pultrusion industry. This monograph will describe the current status of the pultrusion process and the opportunities for innovation which can address current technology gaps.

Key words: circumferential winding; continuous processing; in-line quality control; pultrusion; resin impregnation; thermoplastic pultrusion; thermoset processing.

1. Introduction

The pultrusion process is a continuous method of manufacture of fiber-reinforced plastic profiles having constant cross-sectional area with respect to the length of the product. Products produced by this method are capable of achieving a fiber volume fraction of up to 60%. Lower fiber volumes can be processed as well, as long as the total solids content of the product (fibers and inorganic particulate fillers) is sufficiently high to allow packing of the die cavity for reproduction of the profile details.

The typical composition of pultruded products in high-volume applications today is based upon glass fiber reinforcements in a combination of reinforcement styles such as axial rovings, continuous fiber random orientation mats, and oriented fabrics. The matrix materials are thermosetting polymers of the unsaturated polyester, vinyl ester, and epoxy families which are transformed from their initial low viscosity liquid state to a rigid thermoset polymer state as a result of a thermally induced polymerization. This transformation occurs within the confined environment of the pultrusion die at a rate determined by the kinetics of the polymerization and the length of the reactor—the pultrusion die. Basic to the technology of pultrusion then is the ability to saturate fibers, combine them into a consolidated form prior to die entry (preforming), induce a thermal polymerization reaction within a pultrusion die, and draw the solid cured profile through the die at a constant rate. All of the variations in materials, impregnation methods, die design, and machinery revolve around this basic process sequence [1].

The industry has done well in building a sizable market by applying the best selection of commercial materials as they arrive in the marketplace and by refining methods and machinery. Established markets will continue to grow through additional application opportunities brought to processors by enlightened designers. The industry will expand its technology base by challenging the very basics of the process. The technology of pultrusion in the next 10 years will be marked by innovations in processing methods and materials, resulting in thousands of new applications produced by a highly cost-efficient manufacturing method that can produce engineered materials designed specifically for the end-user. To understand our potential for innovation, we must understand our foundation. A state-of-the-art review follows with the intention of identifying technology gaps requiring technical innovation.

2. Process Description

The term *pultrusion* describes the basic method of manufacture which consists of pulling a reinforcing material through a reactive liquid resin, through a forming device, and into a heated machined-steel die. The material undergoes a chemical reaction causing solidification prior to exiting the die. The solid product is pulled continuously by the pulling mechanism and is then automatically cut to the desired length with a flying cutoff saw. A basic tenet of this process is that a high fiber reinforcement content is required. Furthermore, the fibers must be of high strength and low elongation with thermal stability at processing temperatures in order for products to be pulled without deformation or fracture of the resin matrix. The cross-sectional dimensions of the profile are not determined by the processing rate, temperature, or pulling force, as with thermoplastic extrusion, but rather by the shrinkage of the resin system as a result of cure and by the dimensions of the die. In this respect only, the process is similar to compression or injection molding where cavity reproduction requires a specific volume packing of the cavity. It is of paramount importance in the pultrusion process to use the proper combination of fibers and particulate solid fillers to provide a pressure against the die cavity wall. Without such physical contact, the liquid resin will gel at the die surface to form an unreinforced sheath which will remain in the die. As fibers pull past this sheath a rough surface on the product will result, and a periodic sloughing of the resin sheath will occur. Thus, in pultrusion, it is not possible to produce as low a fiber content as can be found in other static molding methods. Nor is it possible to produce regions of resin richness (low fiber content) without the use of layers of synthetic fiber surfacing veils, such as polyesters or nylon.

The transformation of liquid resin to solid polymer occurs under dynamic conditions within a die which is typically between 36 and 60 inches long. The die is heated either with electrical resistance heaters or a fluid heating medium to a temperature which will allow decomposition of catalysts to initiate the polymerization reaction. The reaction, once initiated, will continue in the presence of a reactive monomer or oligiomer to produce a thermoset cross-linked structure without by-products of reaction. Such reactions are exothermic in nature, and the evolved heat is utilized to take the reaction to completion. By modifying the heat input for initiation and the heat transfer after exotherm, one can significantly alter the processing and quality characteristics of the finished product. The objective, of course, is to produce the highest quality part, free of defects, at the highest possible process speed or throughput rate.

The first process engineering challenge then is to optimize the resin formulation and process parameters utilizing techniques that allow one to track the effect of chemistry changes on reaction position within the die and on the degree of cure. As the curing reaction is significantly different for thin versus thick profiles or open versus hollow profiles, the chemistry and process parameters are significantly different as well. The composites design challenges include the selection of proper fiber types and styles of reinforcement and the placement of reinforcing fibers in the proper position within a profile to obtain specific properties. The ultimate performance of the application will depend upon how well the composite was engineered for the physical, mechanical, and environmental requirements of the application—not upon how fast or efficiently the composite was produced. Finally, the host of mechanical and method engineering tasks necessary to properly collimate materials, impregnate the fibers, preform the saturated materials, and then pull, cut and post-process the finished product are challenges that in general apply to all pultrusions. The specific combination of employed techniques varies widely from profile to profile and processor to processor and is generally a well-protected technology.

3. Success in the Market Place

Many processors have assembled the right combinations of materials, techniques, and process equipment in order to supply the market with a tremendous variety of products. The versatility of the process has enabled pultruded products to be successfully applied in the electrical, construction, corrosion, transportation, marine, consumer, and aircraft/aerospace markets. The successes in these markets are generally the result of the specific advantages of composite materials that provide improved performance when compared to traditional materials. These benefits may be one or more of the characteristics of these materials such as corrosion resistance, electrical insulation, thermal insulation, dimensional and thermal stability, and high strength to weight ratio. Some of the high-volume applications that have successfully capitalized on these features are shown in table 1 [2]. While in some cases pultruded profiles can provide a lower cost alternative, these products rarely are sold on cost advantage alone but rather as a result of the unique properties they deliver. Worth mentioning is that many of the listed applications could not have been produced by any other process simply by virtue of the long seamless length required for the application.

Table 1. High-volume pultrusion applications

Application	Primary benefits
Ladder rails	Electrical insulation
Oil well sucker rods	High strength to weight, corrosion resistance
Industrial grating systems	Corrosion resistance, high strength
Handrail and support systems	Corrosion resistance
Electrical utility insulators	Electrical insulation, high strength to weight
Transformer spacer rod	Electrical insulation, thermal stability
Electrical cable tray	Electrical insulation, corrosion resistance
Standard structural shapes	Corrosion resistant, high strength, flame retardance
Transit third rail cover	Electrical insulation
Tool handles	Electrical insulation, high strength

There are some market areas that are still not easily or economically addressed due to the limitations of today's technology. A few of these are listed in table 2. In some cases, hybrid processes for constant curvature pultrusion or variable cross-sectional profiles (e.g., pulforming) have been developed but are not yet commercially significant or are dedicated to a single product [3]. Other limitations in capability derive from the current raw materials available or the general nature of thermosetting plastic. Opportunities exist in the development of materials and processing techniques that help bridge the performance or application gaps listed.

Table 2. Current performance/application gaps

Profile characteristic desired	Limiting factors
Non-linear, irregular curvature	Process, tooling, equipment, thermosetting polymer
High speed automated fastening	Thermosetting polymer
Controlled twist, thread strength	Process, tooling, equipment, materials
Post-molding modification	Thermosetting polymer
Variable cross section (linear)	Process, tooling, equipment
Service temperature above 400 °F	Materials
High pressure/low permeability pipe	Materials, process
Thin wall profiles (below .060 inch)	Materials, process
Impact damage tolerance	Materials
Low combustibility, toxicity	Materials

4. Materials Overview

The supply of alternative raw materials has broadened dramatically in the past 10 years. With the guidance of the pultruder, the raw material suppliers have tailored materials specifically for the process. The commitment of many of the serious suppliers is demonstrated by their investment in a pultrusion processing capability within their research or application development laboratories. These suppliers can provide additional off-line support for processors to help solve their customers' problems or expand their material data bases.

4.1 Matrix Materials: Thermosetting

The major volume of pultruded applications are based upon unsaturated polyesters, vinyl esters, and epoxies. These resins as listed are in order of their market share. Within the polyester resin family there is a broad range of products from which to choose. The options offered include variations in reactivity, viscosity, elongation, shrinkage, thermal stability, flammability, UV resistance, corrosion resistance, and mechanical properties. The processor chooses the resin initially for its property contributions and secondarily for its processability and cost. The polyester resins are the most commonly employed resins as a result of their combination of excellent properties, ease of processing, and low material cost. Vinyl ester resins are selected for improved corrosion resistance and higher temperature capability, but the processor pays for both a higher raw material cost and the cost of lower productivity due to the slower reaction rate of these resins. The epoxy resins are the highest performance materials in areas of mechanical properties and especially in elevated temperature properties, but they also have the highest raw material cost and slowest process rate. This slow cure rate and the adhesive characteristics of the epoxies make these resins the most difficult to process and, therefore, the most costly to process. Special processing techniques different from those employed for polyester resins are required to successfully process these materials [4].

In general, the more reactive the resin, the easier the resin is to pultrude, since the ability to rapidly form a strong gel allows the resin to release from the die wall without fracturing even under the continuous pulling motion. This feature is exhibited with methacrylate vinyl ester resins recently introduced for pultrusion where line speeds 50% to 100% faster than those possible with polyester resins have been attained [5]. These resins can be highly loaded with fillers and exhibit excellent surface finish and significantly better flame-retardant properties compared to polyester resins. The higher raw resin cost, twice that of polyester, is offset somewhat by the high filler contents possible and higher line speeds (which translate into lower process costs). The high volatility and low flash point of the methyl methacrylate monomer does introduce the need for special environmental controls for operator hygiene and plant safety.

While the methacrylate resins offer significant improvement in flame-retardant properties, the most promising performance in this area is expected from phenolic resins modified for use in pultrusion. Products based on phenolic resins have been demonstrated to have reduced combustibility, extremely low smoke generation, and few toxic byproducts in fire incidents. These resins can also exhibit high temperature property retention equivalent or superior to epoxy resins. These features make phenolic pultrusions particularly attractive in construction, mining, aircraft, and military applications. However, processing difficulties result from the by-products of phenolic reactions—water and ammonia. These gases evolved during curing result in a porous composite structure and lower physical properties. This characteristic, along with the need to utilize reinforcing fibers having phenolic compatible sizings, has slowed the introduction of this resin. Additional complications of short resin pot life and corrosive action on dies have presented other processing concerns to be resolved. Currently efforts are directed at improving the resin/fiber compatibility, evaluation of direct die injection impregnation, and exploration of alternative catalyzation chemistry that will address these problems with phenolic resins [6]. It is expected that with these problems solved, phenolic pultrusion technology may become a significant volume market in the next 5 years.

Other high-performance thermoset resins such as bismaleimide (BMI) resins are being evaluated for advanced composites applications. The motivation here is to provide higher temperature performance and damage tolerance for military and aerospace applications. Many of these high-performance resins are high viscosity or even solid materials at ambient temperature and require special processing techniques to ensure impregnation.

4.2 Thermoplastic Matrix Options

All of the resins mentioned until this point have been thermosetting. The pultrusion process has been successful based upon the ability to saturate fibers with low-viscosity liquid resins which transform to a very high viscosity (solid) phase in the die and provide the strength and shrinkage necessary to release from the die wall. Thermoplastic resins offer improved product toughness due to higher resin elongations and also offer the prospect of post formability of products after molding. High-performance thermoplastic matrices such as polyphenylene sulfide (PPS), polyetheretherketone (PEEK), polyimide, and polysulfone are resins that provide superior high temperature properties when compared to typical epoxy resins. The processing methods required for thermoplastic pultrusion are considerably different, since these materials are solid at room temperature and must be heated above their melting points to flow sufficiently for fiber impregnation. Even when melted, these materials are very viscous and require pressure and mechanical spreading of the fibers to obtain wet-out. Accordingly, investigations of alternatives to hot melt impregnation methods are very active at this time. Techniques in various stages of development or commercialization include conventional bath impregnation with solvent solutions of polymer or aqueous suspensions of small particle solids [7], application of dry polymer particles in fluidized air beds, in-situ polymerization from reactive monomers [8], and hot melt impregnation with low-viscosity, low-molecular-weight cyclic polymers which polymerize to high polymer at high temperatures in the presence of a catalyst [9]. Most of these approaches to date have been limited to production of small strips (tows) or rods which are gathered or chopped to be used as input raw materials in secondary molding operations such as injection or compression molding to obtain long-fiber-reinforced products [10].

An especially promising direct processing approach is based upon a raw material consisting of a combination of thermoplastic resin fibers and reinforcing fibers which have been prepared by the fiber supplier in a manner such that thermoplastic fibers surround each reinforcing fiber. This material form, termed commingled fibers, has the advantage of ease of formability and dry processing as well as the ability to produce larger profiles, since gross impregnation is already accomplished by the fiber producer, and the need to spread and work the fibers for impregnation is greatly reduced. To complete the process, it is necessary to melt and flow the resin fibers while consolidating the materials, eliminating air voids, and establishing good interfacial bonding of resin to fiber [11]. In a similar approach, pre-impregnated (prepreg) tows produced by one of the basic methods previously described can be used as a conventional input material where multiple tows would be combined to produce larger cross-sectional profiles. One disadvantage of this approach is the stiff nature of the pre-impregnated material which hinders the formability that is necessary especially when more complex profile geometries are considered [12].

Processing challenges are numerous with thermoplastic materials, and the industry is only at the initial stages of development of this technology. The process equipment and tooling needs are considerably different and require innovative approaches to ensure uniform melting, collimation, consolidation, and solidification of the thermoplastic composite raw materials. The motivation for pursuing this technology comes both from the marketplace and from the processor. Performance of thermoplastic composites has been demonstrated to be outstanding in applications requiring toughness. High-temperature thermoplastics can be used at service temperatures above the current epoxy resins with better performance in hot/wet environments. The possibility of locally melting and reforming or fusion, solvent, or ultrasonic bonding of thermoplastic profiles provides application possibilities not previously available with thermoset pultrusions. Processing speeds may eventually surpass those of the thermosets, since the process rate is not dependent upon reaction kinetics as it is with thermosets. This possibility, when realized, may help offset the higher raw material costs found with engineering thermoplastics. The commodity thermoplastics polyethylene, polypropylene, PVC, and nylon have excellent possibilities for direct cost competitiveness with thermosets in areas where their properties are satisfactory.

The processor of liquid thermoset resins by pultrusion has learned to deal with the associated housekeeping, solvent clean-up, and styrene monomer emissions in his plant as a necessary part of the business. However, the prospect of a "dry" process which eliminates the need for process hardware clean-up and liquid solvent and resin waste disposal without volatile monomer emissions, as promised with thermoplastics, is very attractive.

4.3 Reinforcements

The strength characteristics of the pultruded profile will be determined by the type of reinforcing fiber utilized, the orientation within the product relative to applied loads, and the volume fraction of fiber utilized. The majority of products today utilize electrical grade glass (E-glass) fibers in the form of continuous unidirectional tows (rovings), or a combination of rovings and random orientation continuous-strand mats or oriented-fiber fabrics. For high-performance composites, carbon fibers, aramid fibers, and other high modulus inorganic and organic fibers can be applied in similar usable forms. The relative proportion of each of these raw material forms is chosen after consideration of the product strength requirements and in light of processing considerations. (A more thorough discussion of fiber types and options can be found in Reference 1.)

A typical profile is made up of a multiplicity of rovings, mats, and fabrics which are each delivered from a continuous package. The resultant composite structure has a "plied" construction in which the designer can achieve substantial fiber loadings in the processing direction (X) and the cross-direction (Y) or any angular direction within the X-Y plane. The composites produced by pultrusion, however, do not have orientation in the Z-direction (perpendicular to the profile thickness), and as a result pultruded products are limited in interlaminar shear strength to the strength of the matrix resin. Reinforcement suppliers have attempted to address this deficiency by offering materials with some degree of Z-axis orientation. Rovings having this characteristic are termed spun, texturized, or bulked rovings and are useful in providing an increased level of shear strength at the intersection of profile sections such as at the flangeweb intersection in a T- or I-beam structure [13]. Because these materials provide a high resin carrying capacity and greater bulking characteristic they are also useful in filling areas of increased cross-section to prevent sink-marks and in small projections on the surface of profiles that are difficult to fill with continuous strand mats. This type of reinforcement provides only a marginal increase in shear strength, however, since the fibers that are oriented in the Z-direction, whether in a roving or mat product, are confined to a very local area rather than deeply penetrating between adjacent rovings or mat plies.

The best possible Z-axis orientation would be one in which fibers penetrated through the entire profile cross-section effectively tying all reinforcement plies together. This approach is currently being promoted with the use of needling or stitching machinery especially suited for multi-ply composites reinforcements. There are problems associated with this approach, however, such as resistance to resin penetration in thick pre-stitched ply structures, orientation of multiple plies in variable thickness cross sections or multiple ply widths within one profile, and the need to prepare such materials off-line, which results in a higher material cost. As such, this approach may be limited to high-performance composites applications which can bear this cost differential and benefit most from the increased strength. In the meantime, Z-axis strength in pultruded composites is an area needing additional innovation from raw material suppliers and processors.

The use of thermoplastic fibers in conjunction with reinforcing glass fibers in a conventional thermoset matrix is an approach which provides a level of increased composite toughness without the processing difficulties associated with thermoplastic matrix pultrusion [14]. Higher impact strengths and greater damage tolerance are a result of the fibers tendency to draw rather than fracture under impact load. There is a sacrifice in composite tensile strength and modulus, however, as fiber volumes normally taken by reinforcing fibers are allocated to the lower modulus thermoplastic fibers. The ability to provide fabrics with specific locations and quantities of any fiber type has led to maximum flexibility in designing hybrid composites. The myriad of choices, on the other hand, is somewhat confusing to the processor or designer who must select the optimum cost/performance material for his or her application.

4.4 Additives and Surface Treatments

Additives are small components of a resin formulation that provide important contributions to composite performance or processability. Common additives include filler, pigment, mold release, flame retardants, low profile agents, catalysts, inhibitors, air release agents, and impact modifiers. The combination of available ingredients in a formulation or recipe is another well-guarded secret that can secure a competitive edge in cost or performance for the processor. However, the resin manufacturers have done a great deal of investigation in this area in order to promote their resins, and pretreated formulations are available from these suppliers to address most applications. Areas where performance gaps still exist that could benefit from improved additives are ultra-violet degradation resistance, flame retardance, improved toughness, and surface smoothness.

Many product applications require surface treatments that provide additional special characteristics not achievable through current additive technology. Pultruded composites utilized in outdoor applications at this time are still best protected from UV degradation or discoloration by an application of a clear or pigmented coating in a secondary operation. Polyurethane and acrylic based coatings have been applied successfully with good results. However, the concern over volatile organic emissions of coatings and the desire for smoother surfaces has resulted in investigations into methods of applying 100% solids coatings as powders, reactive coatings, or extrusion melt coatings. It is anticipated that significant new levels of performance will be achieved through these approaches.

An alternative to coating is synthetic surfacing veils, typically polyester fiber, which provide a resin rich surface and provide a barrier to fiber exposure as the resin degrades. These veils can be pigmented by the supplier to provide additional depth of color and color retention. Another advantage of veils is the ability to incorporate a decorative pattern, customer logo, phone number, patent number, or safety instructions directly in the product during the molding process rather than as a secondary operation. Of additional benefit to the processor is the reduction of die wear obtained from location of the softer synthetic veil between the abrasive glass fibers and the steel die.

5. Process Equipment and Control Technology Highlights

Turnkey pultrusion equipment is available from several U.S. and international suppliers to assist new manufacturers entering the pultrusion market. One such turnkey system is depicted in figure 1. Many of the manufacturers, however, continue to

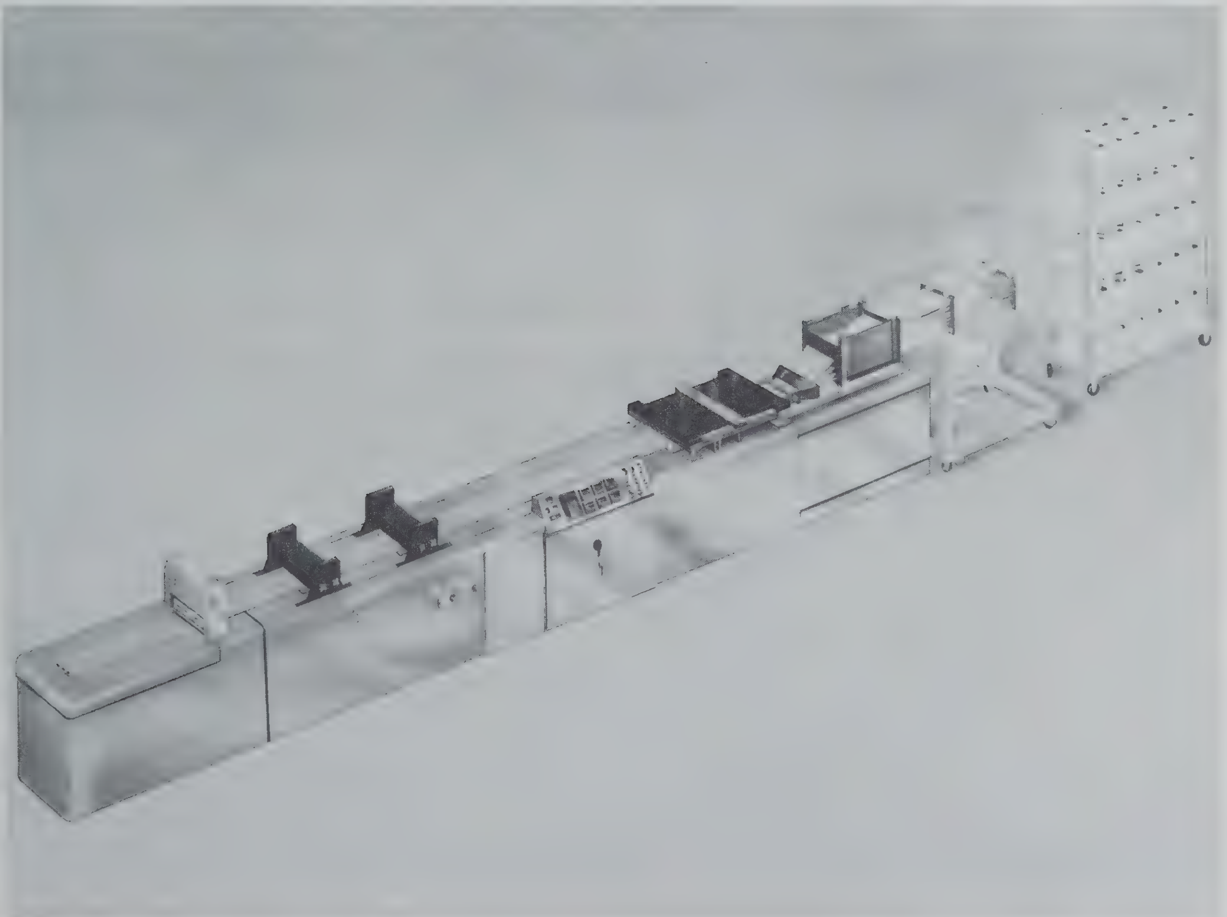

Figure 1. Schematic of a typical turnkey pultrusion line.

fabricate their own equipment, the design of which evolved along with their specific product technology. As a result, there are many functional designs currently in operations with an estimated 400 machines in service worldwide.

Common to all of these systems are material handling stations for rovings, mats, and fabrics (called creels), a resin impregnation station, a die mount and heating system, a pulling device, and a cutoff saw. A successful machine design must provide a controlled delivery of energy to the die, maintain a constant speed pulling motion, and provide adequate pulling force to overcome the resistance of material being pulled through the die. The puller gripping method must provide sufficient force and friction to prevent slippage of the product being pulled and at the same time distribute clamp force so as not to damage the product. The control panel of the pultrusion machine not only must provide control of sequential functions of the machine but also be an effective operator interface to establish and interrogate key process parameters (fig. 2). The emergence of sophisticated display capabilities has allowed for even more meaningful graphical presentation of process parameter status (fig. 3).

The ability to produce a quality product will depend upon the consistency with which the pultrusion machine can maintain process setpoints of temperature and speed. This assumes that the raw material reaction characteristics are consistent as the material is delivered to the process. However, while there has been a great deal of progress in the introduction of machine control sophistication, a machine does not yet exist that can automatically modify its process parameters as a function of either raw material input characteristics or finished product quality characteristics. This ultimate objective, closed loop process quality control, is get-

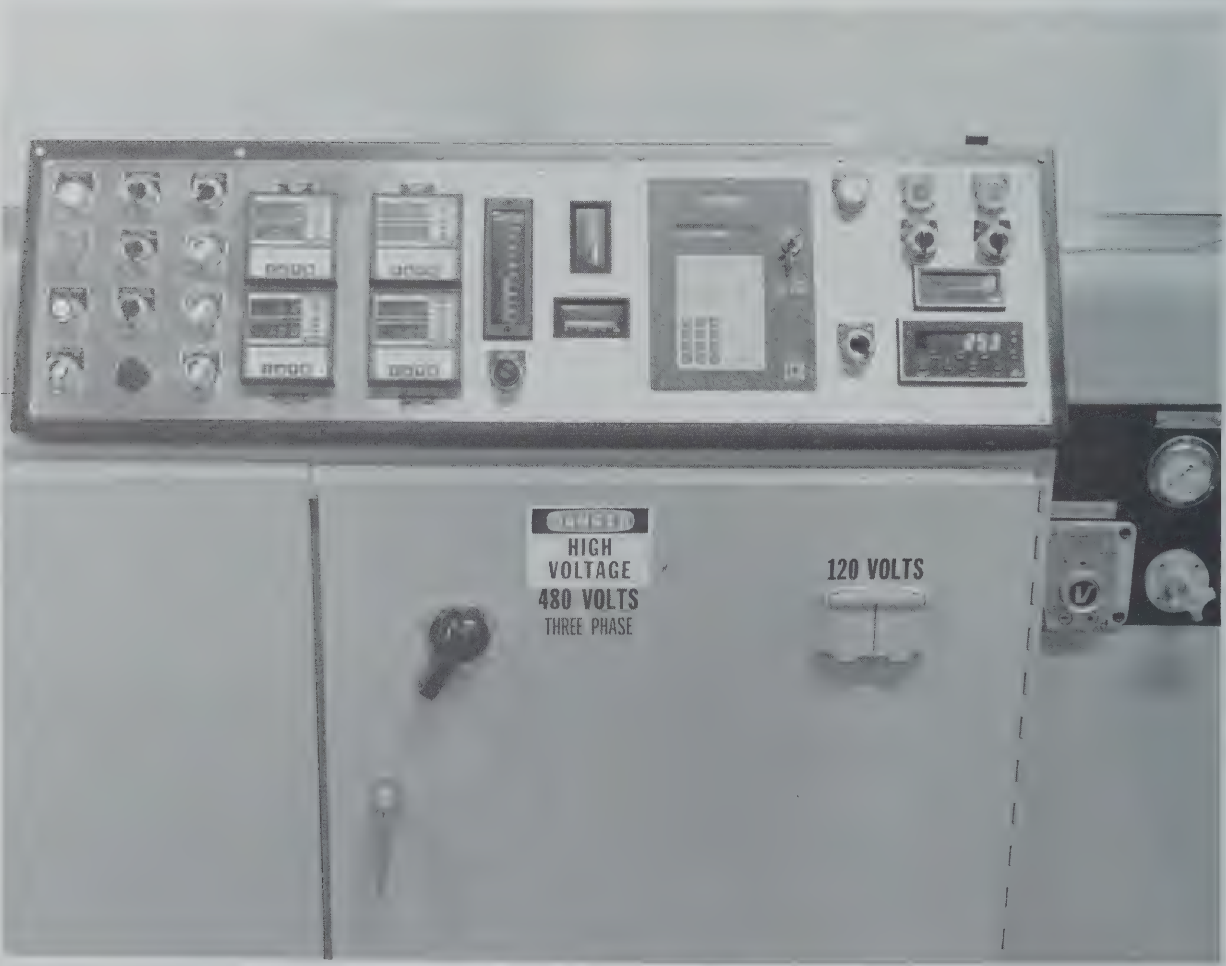

Figure 2. Typical operator control pannel for a pultrusion line.

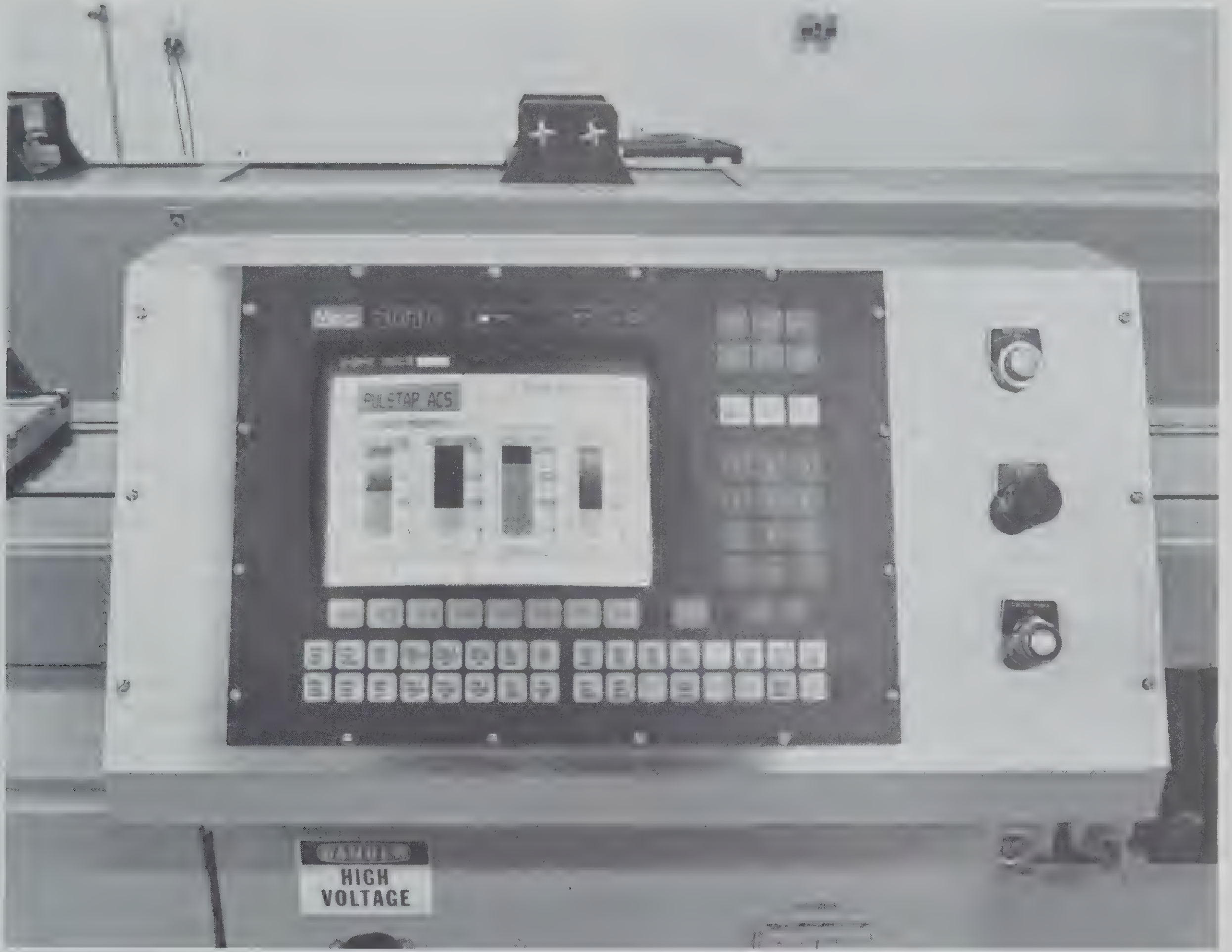

Figure 3. Typical graphical displays now available for pultrusion equipment.

ting closer as more research is conducted on process parameter correlations and the application of new electronic measurement techniques. In the meantime, the processor must rely upon the use of available off-line tools and techniques to determine the raw material reaction characteristics, to establish the effect of process parameters on the reaction dynamics within the pultrusion die, and to measure the resultant properties of the product produced. The process operating window that results must be sufficiently large to prevent minor process variations from causing large variations in product properties. One method of arriving at the process/property window with reduced experimentation is the application of an incomplete factorial designed experiment methodology which allows for testing of minimum and maximum conditions of selected independent variables while testing for correlation to a dependent physical property [15]. However, even this approach is more involved than desired in the typical processor's environment.

As the fundamentals of the process become better understood, predictive mathematical models have been proposed which may allow for off-line process simulation and optimization of process parameters [16]. Often these models employ simplifying assumptions which limit their direct applicability to simple geometries; however, it is anticipated that these current deficiencies will be overcome, and computer modeling will become an important tool in process optimization and ultimately in determination of product economics.

5.1 Temperature Controls

The control of process temperatures has become one of the most precise functions of a good commercial machine with the advent of PID temperature controls. These devices control a process temperature to within 2 °F of setpoint, provided sufficient heating power is made available. The majority of processors employ resistance heating devices placed either within the die or on the die surface or within a heat transfer device such as a platen or heating jacket. A smaller number of processors employ a heating medium such as hot oil, water, or steam to provide energy to their dies. There is not universal agreement as to "the best" method of heating or even the best location for temperature control feedback thermocouples, but this topic is currently the focus of considerable study [17]. What has become acknowledged through studies of the thermal demands of different profiles is that temperature control and monitoring can be applied to advantage in areas other than the die, such as in the control of mandrels in hollow profiles, preheating of input glass or resin, selective cooling of the die entrance or exit, and post-curing or cooling of the pultruded product before gripping [18]. The pultrusion machines produced today are often equipped with multiple zone temperature control and monitoring features with both heating and cooling capability to address all of the possibilities likely to be encountered. This capability is absolutely necessary in machinery capable of addressing the higher temperature demands (up to 750 °F) of thermoplastic processing.

5.1.1 Reaction Characterization While the processor can easily observe the control of the external temperatures applied to his system, it is not possible to observe the response of the raw materials to these temperatures without additional characterization efforts. Monitoring thermocouples placed close to the cavity surface have only limited usefulness, since a discrete number of thermocouples and fixed placement are often a compromise to the need for a continuous internal temperature readout and flexibility in cross-section placement. The accepted method of evaluating the progress of the polymerization reaction inside the die is to insert a sacrificial thermocouple into the center of the material as it enters the die and then to monitor the temperature of the material as it passes through the die. This information is then related to the die position in order to determine the point of initiation of the exothermic reaction, the position of its peak temperature, and the temperature of the material as it exits the die. Under steady-state conditions of speed and input temperature, this internal exotherm profile will remain constant. The effects of changes in process speed, die temperature, or chemistry of the resin can easily be evaluated using this technique. Automated instrumentation has been developed to provide this information quickly and economically for engineering, production, or QC purposes (fig. 4) [19].

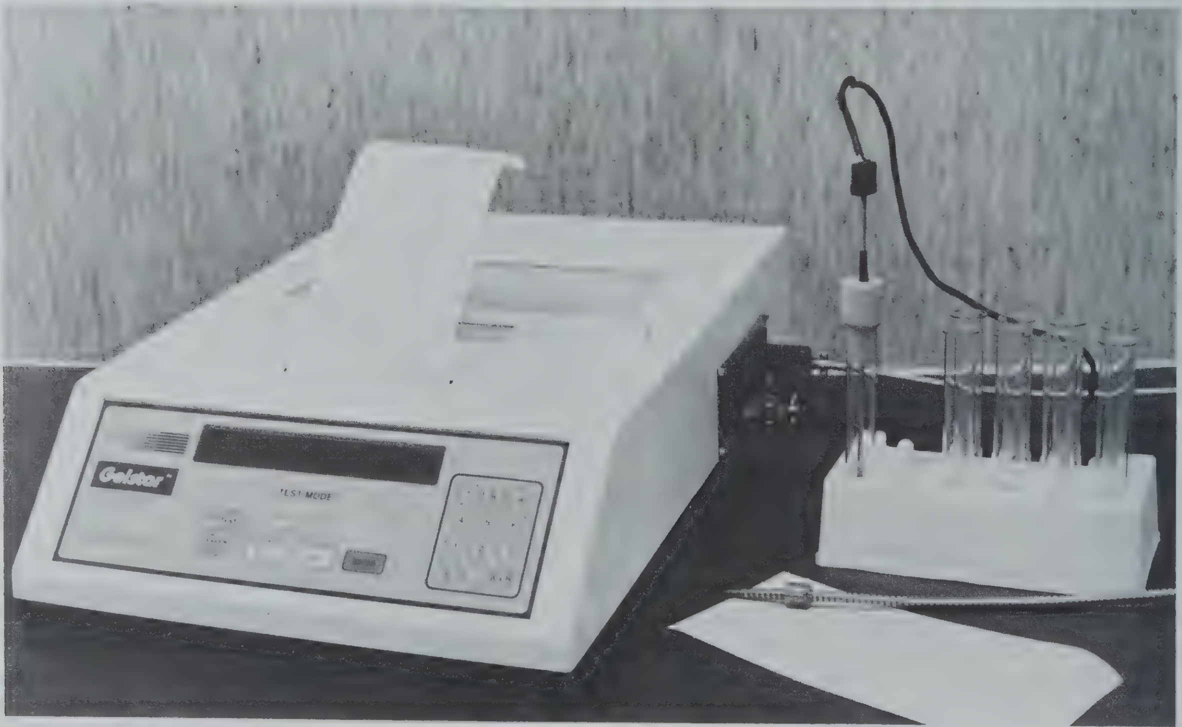

Figure 4. Typical automated instrumentation currently used for engineering, production, and QC purposes.

This method of characterization utilizes the exothermic heat generation as a measure of the completion of reaction, but it represents only a periodic "snapshot" of the reaction conditions. A more direct measurement would look at a characteristic of the material itself such as a change in dielectric constant as the material cures. Such a system is under development for application as a continuous process feedback parameter and may allow for true closed-loop control by adjustment of speed or temperature to maximize the degree of cure [20].

5.2 Speed Control and Pressure Influence

Since the control of speed is essential to providing consistent residence time of the material in the die, the machine puller drive system is an important consideration. There are various styles of pullers in commercial use, including opposing drive wheels, belted or cleated chains, and mechanical or hydraulic reciprocating clamps. Regardless of the puller type, the drive control should employ a speed feedback device to eliminate speed sensitivity to pulling load changes. Such devices would include speed tachometers, stepper-motor encoders, and hydraulic servo or proportioning valve loops utilizing linear displacement transducers. Normal processing conditions can cause an increase in pulling load, resulting in a tendency to stall the machine. If adequate clamping pressure is not provided, then the product may slip within the grippers even though the pulling speed of the machine may be maintained. For this reason, it is desirable to have speed feedback signals originate from a device linked to product speed rather than machine drive speed.

The pressures within the pultrusion die arise from frictional resistance of the liquid, gel, and solid regions within the die and as a result of the volumetric packing of the die cavity. There is a direct relationship between line speed, and pulling resistance. The ability to measure internal pressures has been explored with the use of die cavity transducers, sacrificial force sensing resistors, and pressure sensitive fiber optic sensors [21]. The periodic measurement of internal pressure distribution within the die in the same fashion used to generate internal temperature profiles has been shown to be useful in characterization studies [22]. The continuous measurement of internal pressure, though potentially useful as a feedback parameter, has not yet been applied successfully. A continuous display of external pulling resistance is useful to monitor the stability of the process, since pulling resistance changes can be caused by changes in process parameters, resin cure, or reinforcement volume.

5.3 Questions and Answers

As with other process industries, the availability of signal conditioning and data reduction hardware and software packages has enabled the systematic study of the pultrusion process. High-capacity storage media allow for the collection of high volumes of process data for interpretation in flexible spreadsheet-type formats or in fixed formats such as SPC (Statistical Process Control) range and mean deviation trends. The more flexible the software system, the more input the processor must supply to configure a meaningful report. The emergence of "canned" software programs specifically for pultrusion process analysis is expected to be an area of participation by firms having similar tangent applications. An interactive graphic display device has recently been introduced that allows for direct observation of line speed and pull load trends and provides alarm outputs for operator response [23]. The external load signal can be derived from a drive motor amperage, a hydraulic cylinder pressure, a machine frame strain gauge, or a direct die force transducer. This instrument also utilizes the process speed information to generate useful production efficiency data for manufacturing management purposes.

5.4 Process Enhancements

Innovative processors have added a variety of enhancements to the basic pultrusion process to form unique product forms. Among these are the continuous encapsulation of wires, wood, foam, and other insertable materials. Discontinuous inserts are joined either manually or automatically to provide a continuous feedstock. In this manner, the finished product can exhibit special properties not achievable with the composite material alone. Examples of such products include CB antennas (wires), electrical maintenance tools (foam core), and automotive drive shafts (aluminum tubing).

Another enhancement which has had renewed interest recently is the addition of continuous wound fibers to tubular profiles. Either circumferentially wound or braided fibers can provide an additional level of performance in crush, burst, or torsional strength of tubing above that of conventional mat and roving constructions [24]. The level of performance, however, is still substantially below that of filament wound tubing in applications requiring fluid containment at high pressure. Significant improvements in both materials and process would be required to be competitive in this area.

Other in-line process enhancements are attractive to processors, since the relatively slow process speeds of pultrusion (l to 6 ft/min) allow considerable time for secondary functions. Application of labels, paint, clear coatings, slitting, punching, and sand blasting are all operations which have been performed in-line on various products. The advantage of reduced handling and labor economies, however, must be weighed against the possibility of adding complexities which could result in increased down time.

6. Tooling Insights

Pultrusion dies are precision ground tool steel cavities which are typically 3 to 6 feet in length. The cavity is highly polished for good release and most frequently hard chrome plated for lubricity, corrosion, and wear resistance. Through-hardened steels have also been utilized with some sacrifice in corrosion resistance, workability, and damage tolerances; however, substantial increases in die life can result. The wear characteristics of a tool will depend largely upon the amount and type of fiber and filler employed in the profile but can also be influenced significantly by the accuracy of preformed material placement. The industry is always on the lookout for improved tooling steels or surface treatments such as high energy implantation or coatings that can provide extended process life to dies since both the original cost of tooling and subsequent rework expenses are a significant part of the per-foot cost of producing a profile.

The profile design determines the number of pieces employed in a die and the location of parting lines where the die pieces are joined. Due to the internal pressures of the process and this multiple piece die construction, all dies are integrally bolted rather than held together with a clamping device such as is utilized with compression molding press platens. As a result the procedure for cleaning and inspecting a die cavity is a lengthy one which must be performed off-line and on occasion is hindered by the die size and weight. An experienced die designer must consider this processing requirement along with the more obvious considerations of shrinkage, draft, taper and tolerances when designing pultrusion tooling. The design of pultrusion dies can be easily addressed with a computer-aided design (CAD) system, since many of the tooling features are repetitive.

Forming guide technology, on the other hand, is a highly specialized discipline which comes from years of process experience and a sound basis of composites design principles. The design of a forming system cannot start without a knowledge of the exact composition of roving, mats, veils, and fabrics. The orientation of the material as it passes through the impregnation process is an important design factor as well. Impregnation, removal of excess resin, gradual collimation, and proper fiber distribution are all issues that must be addressed during the design of the forming hardware. As a result of the highly specialized nature and distinctive composition of a profile, it is difficult to apply a CAD program to this aspect of tooling design. It is even more difficult to apply computer-aided manufacturing (CAM) to produce the components of a forming guide system. Most processors rely heavily upon skilled craftsmen for the fabrication of these specialized secondary tooling systems.

7. Quality Control

Quality control efforts must extend to aspects of raw materials, in-process resin formulation and reinforcements, process methods (e.g., dies and preforming), process parameter controls, and finished product physical or mechanical property characterization [25]. Test methods exist for most of these areas that can help ensure consistent products. The biggest gap yet to be successfully addressed is that of on-line identification of composite flaws such as porosity, delamination, internal cracking, or undercure. Sophisticated techniques have been developed for off-line characterization, such as ultrasonic C-scan or x-ray inspection of advanced composites structures used in aircraft and military applications. The high capital costs of these techniques, along with the difficulty of coupling sensors to a moving continuous profile, have precluded the on-line application of these methods in pultrusion. Accordingly, the pultrusion machine operator is still a critical link in the process, and visual inspection of each piece is a necessary procedure for 100% certainty in quality assurance. Some aspects of visual external defects, such as a loss of dimension of a profile or the appearance of abrasion, may lend themselves to currently available automated pattern recognition technology for initiation of operator alarms. While some defects are readily identified, other more subtle defects are occasionally passed in a visual inspection. Once a product is produced, unless it is indelibly marked in some fashion, it loses its traceability back to a production period or raw material lot. This becomes an important consideration in high-liability applications where verification of conformance to standards from historical data is important. An opportunity exists for technology development that addresses this gap.

8. Process Support

With the increasing number of regulations concerning the control of the environment within the factory as well as in the community, there is a need for technologies that address the general problems of the fiberglass producer. Among these are the reduction of airborne styrene levels in the factory, the elimination of toxic solvents, the reduction of waste resin and finished product scrap, and the possibility of converting thermoset resin or scrap products into a useful material through recycling. Such a recycling program is currently under evaluation for SMC and BMC materials where a particulate filler is being produced from thermoset scrap products. Imaginative approaches to these problems will be welcomed by pultruders anxious to comply with regulations while reducing their costs of compliance.

9. Summary

The technology of pultrusion is very broad when one considers all aspects of materials, equipment, and tooling technology. It is difficult to provide more than an overview in a limited monograph format. The references cited throughout the text have been selected to provide a much more thorough exposure to some of the exciting technical advancements in the pultrusion industry. There are many opportunities for firms and researchers to contribute to the growth of the market by expanding the technology base. Some potential opportunities are summarized in table 3.

Table 3. Summary of current technology opportunities

Materials	*Benefit Sought*
Resins	
Phenolics	Low smoke, toxicity
Thermoplastics	Toughness, post forming
High-temperature thermoset	High-temperature, damage tolerance
Fibers	
Z-axis orientation	Improved shear strength
Specialty fabrics, mats	Directional strengths
Additives	
UV Inhibitors	Improved weathering
Low profile additives	Surface smoothness
Flame retardants	Low flame, smoke, toxicity
Surface Treatments	
Paints, coatings	Surface smoothness, weatherability
Adhesion promoters	Paint adhesion
Thermoplastic Co-extrusion	Surface smoothness, weatherability
Processing	
Direct injection impregnation	Reduced emissions and waste
Thermoplastic process	Eliminate emissions, toughness, post forming
Circumferential winding	High-pressure capability
Tooling	Improved wear resistance
Quality Monitoring	Continuous flaw detection, degree of cure
Environmental Issues	Emission control, waste and scrap minimization, recycling

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Corporation (EPIC). Pultrusion Technology became a division of MMFG in 1989 and Mr. Sumerak currently holds the position of Technical Director for this division located in Twinsburg, Ohio.

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Structural Reaction Injection Molding

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A review of structural reaction injection molding (S-RIM) with an emphasis on its manufacturing aspects is presented. An overview of preforming, S-RIM resins, S-RIM processing technology and S-RIM applications is provided. Technology needs and limitations are discussed.

Key words: mat molding; polyurethanes; preforms; S-RIM; structural reaction injection molding; structural RIM.

1. Introduction

Structural reaction injection molding (S-RIM) is currently in its technological infancy. As a consequence, it is simultaneously undergoing dramatic materials and process improvements and rapid industrial growth. In many ways S-RIM is the natural evolution of two other, more established plastic molding processes—reaction injection molding (RIM) and resin transfer molding (RTM). S-RIM uses the fast polymerization reactions of RIM-type polymers, its intensive resin mixing procedures, and its rapid resin injection rates. S-RIM also employs preforms preplaced in the cavity of a compression mold, like RTM, to obtain optimum composite mechanical properties. The basic concepts of the S-RIM process are shown schematically in figure 1.

The ability of S-RIM to fabricate large, lightweight composite parts consisting of all types of precisely located inserts and judiciously selected reinforcements is an advantage that other competitive manufacturing processes find difficult to match. In addition, large S-RIM parts can often be molded in 2 to 3 minutes while using clamping pressures as low as 100 psi (0.7 MPa). Thus, the capital requirements of S-RIM are relatively low allowing the economical manufacture of parts with annual production volumes below 10,000 units. These advantages, when coupled with the concurrent development of a large family of commercially available S-RIM resins, has led to predictions of S-RIM annual growth rates approaching 42% [1].

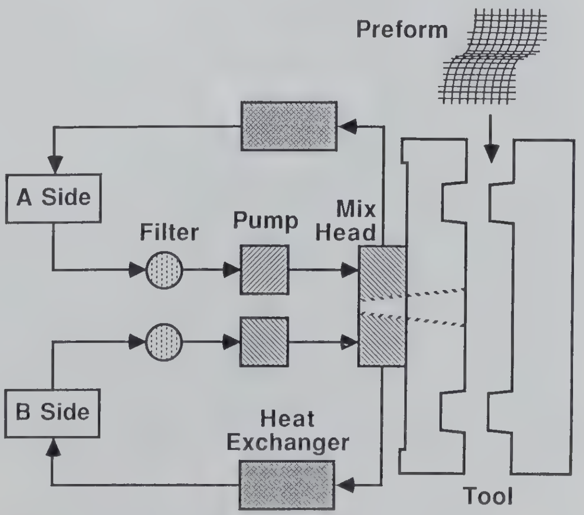

Figure 1. Illustration of the S-RIM process.

2. Preforming

The key to all liquid composites molding processes (S-RIM, RTM, or cold pour molding) is the "preform"; a pre-shaped, three-dimensional precursor of the part to be molded except that it does not contain the resin matrix. Thus, a preform can consist of fibrous reinforcements, core materials, plastic inserts, or metallic inserts.

These reinforcements, cores, or inserts can be anything available to the composites manufacturing engineer which meets the parts' economic, molding, structural, and environmental durability requirements. This tremendous manufacturing freedom allows for a large number of alternative preform constructions.

Since most commercial S-RIM applications have been in general industrial use or in the automotive industry, the reinforcement material commonly used has been fiberglass due to its low cost. This fiberglass has been in the form of either woven cloth, continuous strand mat, or chopped glass.

Space shaping cores can be used in the S-RIM process to fabricate thick three-dimensional parts with low densities. Fiberglass reinforcements and inserts can be placed around these cores, resulting in S-RIM parts which are structurally strong and stiff, can be molded in one piece, and are very lightweight. Specific grades of urethane-based, 6- to 8-pound density foams which are dimensionally stable at S-RIM molding temperatures are commonly used as molded core materials. For applications requiring a core which can withstand high compressive loads, end grain balsa has proven to be suitable.

Metallic inserts have been used in S-RIM parts as local area stiffeners, highly stressed attachment points, or weldable studs. The metallic material of choice has been steel for the majority of these inserts.

Molded plastic inserts have been used in some S-RIM applications to perform very specific functions. VELCRO® strips can be molded on the surface of S-RIM parts as an attachment mechanism to mechanically hold other parts in place. Extruded plastic tubing can be used in S-RIM parts as internal conduits for electrical wires.

While it is easy to visualize a three-dimensional S-RIM preform and then to make a limited number of them by hand, it has proven to be a challenge to make consistently identical, high volumes of these preforms economically. Preforms for RTM and cold pour molding have been made since the 1950's either by directed fiber preforming (DFP) or by a manual "cut-and-sew" process. For low production volumes or for lightly stressed applications, these preforming techniques are suitable for S-RIM. Other more mechanized preforming processes are currently under development for high production volumes.

2.1 "Cut-and-Sew" Preforming

In this process a preform is assembled much as a seamstress assembles a piece of clothing on a dummy. Patterns representing the individual, sectional layers of the part are used as templates to cut pieces of the preform from a roll of the reinforcing material. Woven fiberglass cloth, unidirectional mat, chopped glass mat, and/or continuous strand mat are commonly used in this process.

These cut pieces of fabric are either placed directly into the cavity of the S-RIM mold, mechanically stapled to a core, or placed onto a forming shape. Additional reinforcing fabric layers can then be added if necessary. Metallic or plastic inserts can also be added to the preform. Eventually this preform is placed in the cavity of the S-RIM mold, and resin is injected into it.

Needless to say, this is a very labor-intensive process, and the consistency from preform to preform is usually poor. However, for very low manufacturing volumes this process can be cost effective. It is almost always the procedure used to make preforms for prototype S-RIM parts. For the first production S-RIM part, a spare tire cover for General Motors' C and H body cars molded by Ardyne Inc., preforms die-cut from glass fiber mat have been used since 1985 [2].

2.2 Directed Fiber Preforming

Directed fiber preforming (DFP) is a partially mechanized method for making chopped glass three-dimensional preforms. With this technique, a stream of chopped fiberglass and a binder are sprayed onto a perforated, three-dimensional, metal shaping form through which a high volume of air is being drawn. The resulting fiberglass preform replicates the shape of the perforated screen.

Two distinctive types of DFP machines have been developed: plenum chamber and open spray. They are similar in that a resinous binder and chopped glass fibers are collected onto a screen by air movement. The binder is then cured through the application of heat and the preform is removed from the screen.

2.2.1 Plenum Chamber A plenum chamber preforming system chops glass fibers inside a baffled, turbulent air chamber containing the perforated forming screen. This screen rotates on a horizontal turntable and a high air flow rate is used to attract the chopped glass fibers to the forming screen. One-position, two-position, and four-position forming station machines have been built. Most plenum-chamber forming stations are about 36 inches in diameter, although a two-station machine has been built with forming stations as large as 90 inches in diameter (Emoto Industrial Co., Ltd). Symmetrical or nearly symmetrical preform shapes are best suited to plenum-chamber machines. This equipment also has the advantages of good repeatability and automatic operation but is limited in its production rate [3,4].

2.2.2 Open Spray This equipment is characterized by (see fig. 2):

- a hand-held glass cutter and binder spray unit;
- a vertically rotating ferris-wheel assembly with four individually rotating preform stations;
- a spray station, an oven curing station, a blank station, and a preform removal station;
- a forming station with screens as large as 200 inches in diameter and depths of 3 to 4 feet.

The open spray DFP equipment provides a uniform deposition of fiberglass, minimum overspray, and the ability to fabricate large, complex preforms economically.

The cost of a 120-inch version of this equipment has been estimated at $500,000 (1990 $). This machine is capable of producing about 1.6 million pounds of preform per shift per year with a fabricated preform cost of $1.10 per pound [2]. Recently, a robot has been used to replace the hand spraying of the fiberglass and binder [5]. This automation will enhance the consistency of the chopped glass preform.

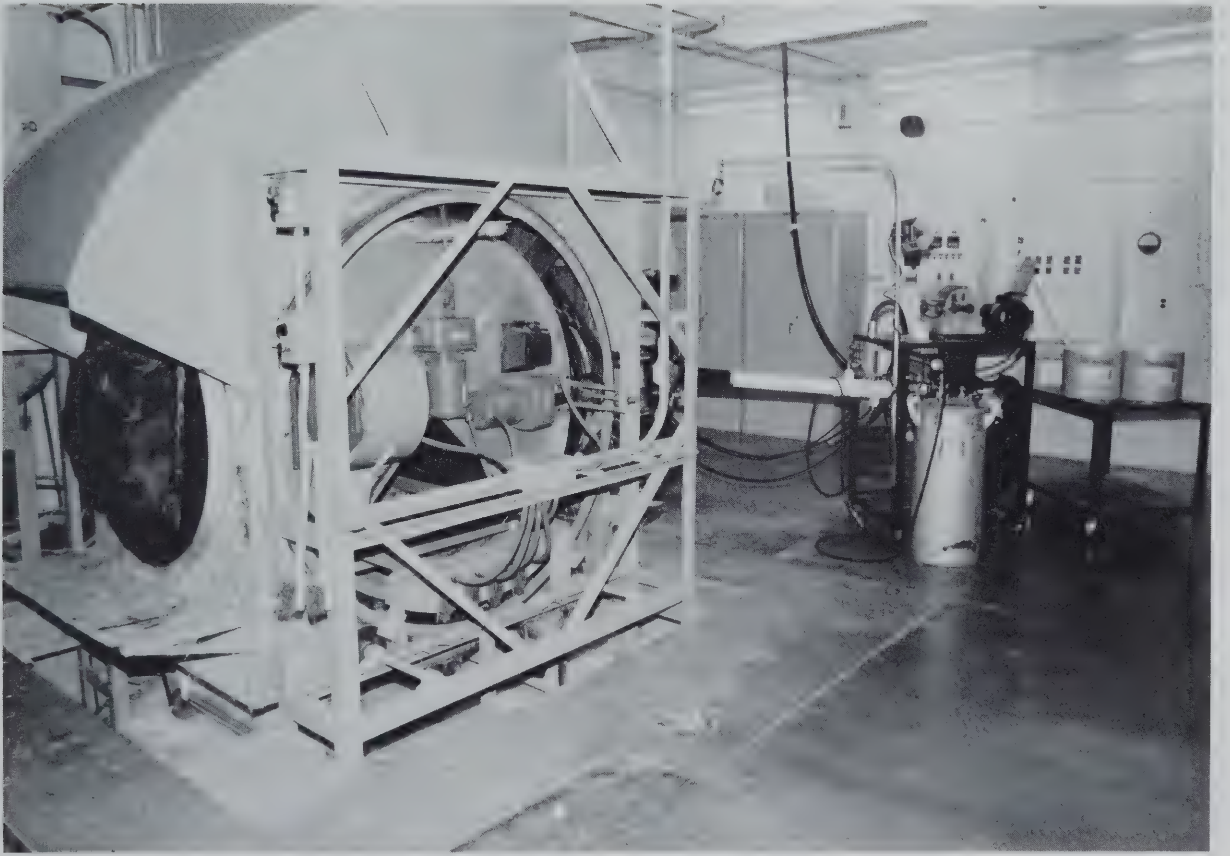

Figure 2. Photograph of an open spray laboratory scale DFP machine (courtesy of Pittsburgh Plate Glass Company).

2.2.3 Other Factors Many solvent and aqueous borne binders have been used to make preforms for RTM and cold pour molding. These preforms have been successfully used with polyester resins and slow resin injection rates. However, most S-RIM manufacturing operations use pH-sensitive urethane-based resin systems and high resin injection rates. The development of appropriate binders which do not retard resin cure or "wash" during molding is crucial to the use of DFP preforms in S-RIM.

In addition, DFP preforms are limited to chopped fiber volume fractions below 28% [6]. Unidirectional glass and fabric can be added to the preform during the chopping process and encapsulated in place to provide enhanced local area properties to DFP preforms [7]. The high loft (due to their low packing density) of DFP preforms makes it difficult to close the cavity of S-RIM molds with preforms which have significant z-direction dimensions without damaging them.

Even with these limitations there has been significant commercial DFP activity in the last few years. Two S-RIM molders (Ardyne Inc. [2] and Davidson-Textron [8]) have been reported as installing DFP machines. The H. R. Edgar Machining & Fabricating Company announced recently that they will begin quoting on the ferris-wheel configuration DFP machines [9]. In addition, Krauss-Maffei has proposed a fully automated S-RIM DFP-to-molding system [2,9]. PPG Industries, Inc., in a recent publication [10] presented a conceptual drawing of a different process to manufacture chopped glass preforms in a semi-continuous operation.

2.3 Formable Mat Preforms

The process for making thermoformable preforms is very similar to that of making thermoformed plastic parts. A large sheet of fiberglass containing a binder which softens under heat is placed in a frame and inserted into an oven for several minutes. This sheet is then rapidly transferred to a compression press and formed into the shape of its mold cavity. The preform is allowed to cool under pressure, so that it retains its shape; it is then removed from the press. After the edges of the preform are trimmed, it is ready for S-RIM molding. The cycle time of this preforming process can vary from 2 to 10 minutes depending upon binder chemistry, mat thickness, and equipment design. The forming molds are made from either wood, cast epoxy, a backed-up nickel shell, cast aluminum, or steel [7]. For production volumes larger than 20,000 parts per year, steel would be the preferred material for the forming molds. Forming pressures in this process are usually below 50 psi.

2.3.1 Formable Mat Materials A thermoplastic-based binder fiberglass continuous strand mat (CSM) is available from both Owens-Corning Fiberglas (OCF M8608-X5) and Certainteed Corporation (Unifilo 750). A formable, thermosetting binder CSM is available from Nicofibers, Inc., (N-700, N-751, and N-754). The Nicofibers CSM material requires heat to *cure* the binder rather than to *soften* it as with the thermoplastic-based formable mats. Thus, a different process and, therefore, different equipment are needed for forming this material.

No mechanical property data of these preform materials in S-RIM composites has been published. Concern has been expressed by some S-RIM engineers that the thermoplastic binders might interfere with the bond between the glass fibers and S-RIM resins.

2.3.2 Thermoplastic Binder Preforming Techniques Several processing techniques have been developed for constructing thermoplastic binder-based CSM preforms [11]: stretch-to-shape, folding techniques, and presser bar.

In the stretch-to-shape process a heated CSM is clamped into a holding frame of dimensions sufficient to allow for a "reservoir" of mat to stretch while forming a shape. As the male cavity mold half hits the clamped CSM, it begins to stretch and form the three-dimensional shape. However, this stretching can be non-uniform, and resulting local variations in fiberglass contents and fiber orientations are possible. Inconsistent stretching of the mat can also lead to non-reproducible preforms [12]. In addition, significant offal (>20%) can be generated around the clamping edge of the part.

Folding techniques can be used to overcome the non-uniformity in stretching in CSM and allow the use of directional fabrics. In this technique selective folds in the mat are made which unfold during preforming. It is also possible to allow the mat to sag into the mold during preforming. These techniques can help to reduce the edge offal 10% to 15%.

Directional fabrics are often required in S-RIM parts to provide higher laminate directional properties. Since directional fiberglass reinforcements are unable to stretch, they have limited conformability. Folds allow these materials to be thermoformed in combination with thermoplastic-based CSM. However, it is difficult to make preforms composed of directional fabrics without wrinkles.

Ardyne Inc. has reportedly [2,13] used a proprietary preforming process to make wrinkle-free bumper beam preforms composed of a woven/chopped mat (see fig. 3). Freeman Chemical Company has developed a thermoplastic binder (Stypol 44-6020) that can be applied to almost any mat which allows it to be thermoformed [7].

Another technique for forming thermoplastic binder CSM uses a spring-loaded presser bar to anchor the hot mat and prevent slippage during forming. The presser bar is built into the top portion of the preform mold. As the mold closes, it makes contact with the bottom half of the mold, freeing the mat to drop, slide in the mold and be formed into the required shape [11].

2.3.3 Thermoplastic Binder Preforming Equipment The EMC Machinery Division of the Snow Corporation has built several large formable mat preforming machines (fig. 4). Their equipment is characterized by the oven moving over the preform frame carriage to save processing time. Controlled zone infrared radiant panels allows for maximum preform flexibility and heat-up rate. A programmed controller is used to govern the forming sequence [4]. A 6-foot×7-foot forming system costs approximately $190,000 (1990 $) [11]. Cannon has reportedly sold a similar preforming machine to Montedison in Italy.

2.4 Textile Process Preforms

The family of textile processes consists of braiding, knitting, and weaving [14,15]. Each can be used to produce S-RIM preforms. They all have the advantage of making complex, three-dimensional, near-net-shape preforms without discontinuities. However, preforms made using these processes are relatively expensive when compared with DFP and thermoformable mat preforms.

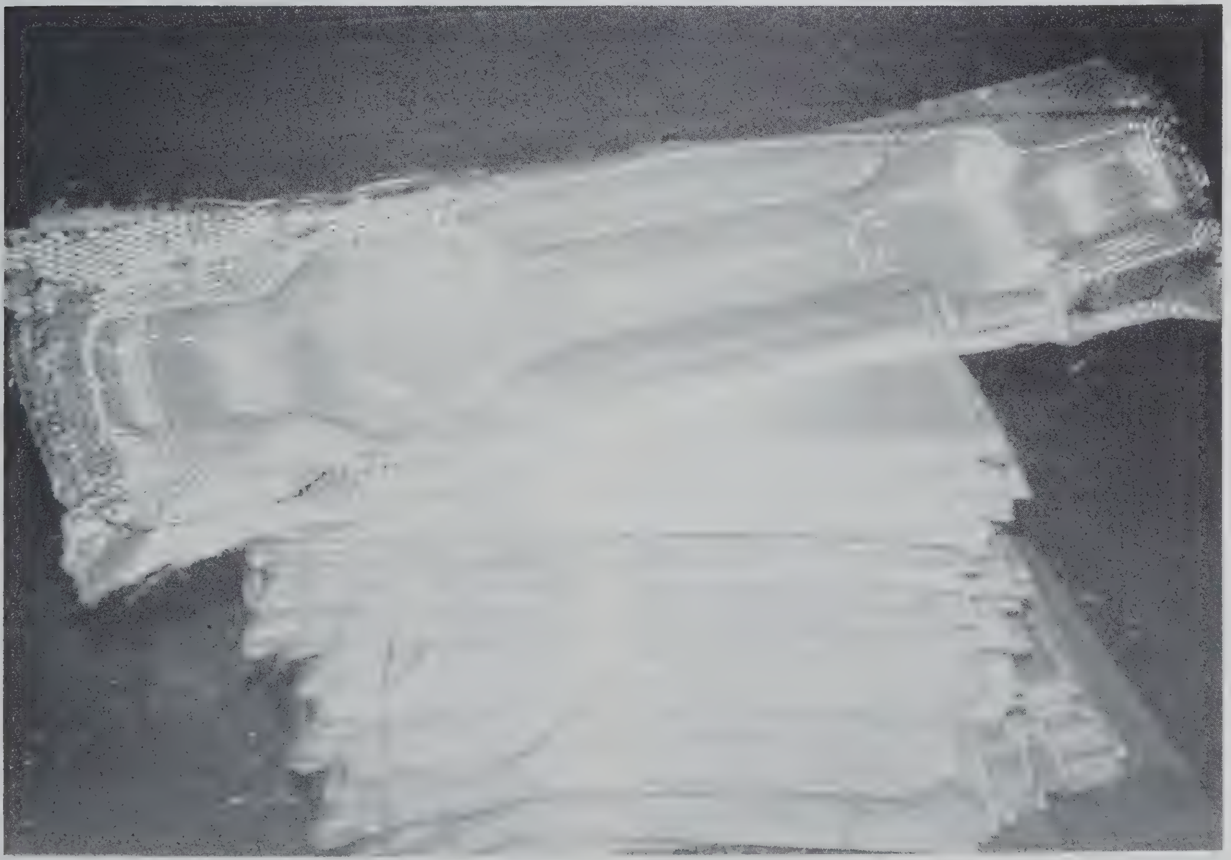

Figure 3. Photograph of a Corvette S-RIM front bumper beam preform (courtesy of Ardyne Inc.).

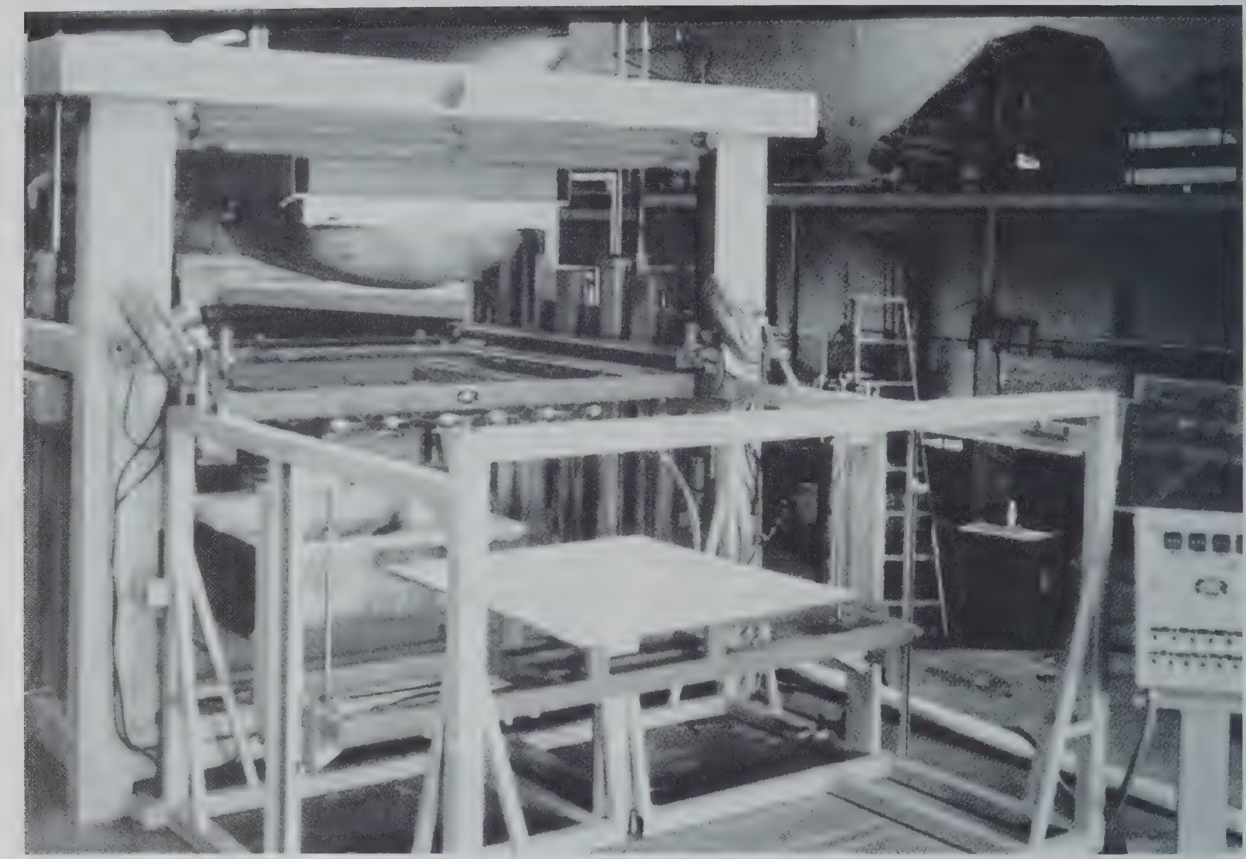

Figure 4. Photograph of a thermoplastic binder fiberglass preforming machine (courtesy of the EMC Machinery Division of the Snow Corporation).

2.4.1 Braided Preforms Braiding is a process whereby yarns are intertwined around each other at a direction bias to the direction of manufacture [15]. The braiding process has been known for centuries, and its automated machinery was invented in the mid-1800's.

In this preforming process, fibers can be either wrapped around a forming mandrel or formed into a free-standing flat braid. Figure 5 shows a braided S-RIM preform formed over a urethane core. The fibers are oriented at angles $+\theta$ and $-\theta$ to the braid axis in most two-dimensional biaxial braids. Introduction of a third fiber in the direction of the braid axis forms a triaxial braid.

The off-axis directionality of a braided solid of revolution offers excellent torsional rigidity. Thus, braided preforms are often used in drive shaft applications. Braiders suitable for making composite preforms are available from New England Butt/Wardwell, Rockwell International, and Steeger USA [16].

2.4.2 Knitted Preforms Courtaulds Research, using computer-controlled presser-foot knitting technology, has developed the manufacturing procedures to fabricate complex, three-dimensional knitted preforms suitable for S-RIM [18,20]. A wide range of preforms has been made consisting of the following basic elemental shapes:

- plane surfaces—zero curvature in all directions;
- cylindrical surfaces—zero curvature along the axis with maximum curvature normal to the axis;
- spherical surfaces—a surface with curvature radiating in all directions from any part on the surface;
- conical surfaces—zero curvature along the axis with varying curvature normal to the axis [18].

These basic shapes can be used either singly or fully integrated into a preform.

In the Courtauld's knitted preforms, a significant amount of the knitted fiber must be in a loop configuration much like CSM. Thus, the moduli of composites containing these knitted preforms

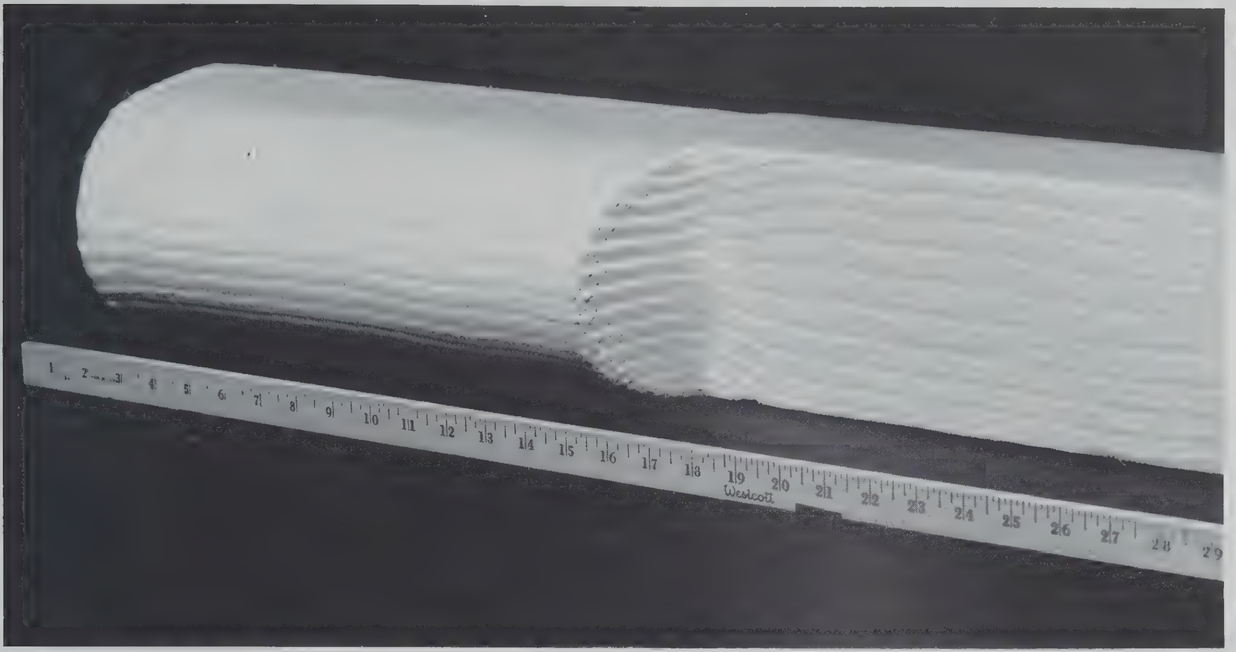

Figure 5. Photograph of braided S-RIM preform over a polyurethane foam core (courtesy of Shell Development Company).

resemble CSM reinforced composites of the same fiber volume fraction. However, the tensile strengths of the knitted composites are lower than those of CSM reinforced composites. The real material benefit of three-dimensional knitted preforms is the elimination of laminate fiber discontinuities which occur at layer junctions of "cut-and-sew" prepared preforms. Other benefits would include: (1) improved reproducibility/consistency, (2) suitability for high production rates, (3) formed to near-net-shape, (4) ease of handling, and (5) the ability to fabricate unique/special features. The cost-effectiveness of knitted three-dimensional preforms for general industrial and automotive S-RIM applications remains to be proven.

2.4.3 Woven Preforms Much like knitting, weaving can also be used to fabricate near-net-shape three-dimensional preforms. However, woven preforms consist of two interlacing sets of yarns perpendicular to each other. The 0° set is called the "warp," and the 90° set is called the "weft."

Thus, the fibers in a woven preform cross over and under each other in an S-shaped path causing a bend or crimp. As these fibers are loaded in tension, they try to straighten out, and eventually they can pull away from the resin matrix. Generally, composites reinforced with woven preforms have tensile strengths, flexural strengths, and fatigue lives only 60% of those reinforced with two-dimensional knitted materials. The stiffness of the knitted composites is approximately 40% greater than that of the woven composites. Woven preforms, however, cost less per pound, and they often conform better to complex surfaces than knitted preforms.

3. S-RIM Resins

The commercialization of a large family of low-viscosity, fast-reacting and economical resins was responsible for the industrial debut of S-RIM. The activities of resin suppliers such as Amoco, Arco, Ashland, BASF, Dow, Goodrich, Hercules, ICI, Mobay, and OCF have speeded the adoption of S-RIM by many molders.

There are several characteristics common among most S-RIM resins:

- Their liquid reactants have room-temperature viscosities below 200 cPs.
- Their viscosity-cure curves are sigmoidal in shape with a typical mold fill time of 15 to 90 seconds (see fig. 6).
- Their demold time is from 60 to 180 seconds, varying with catalyst concentration.

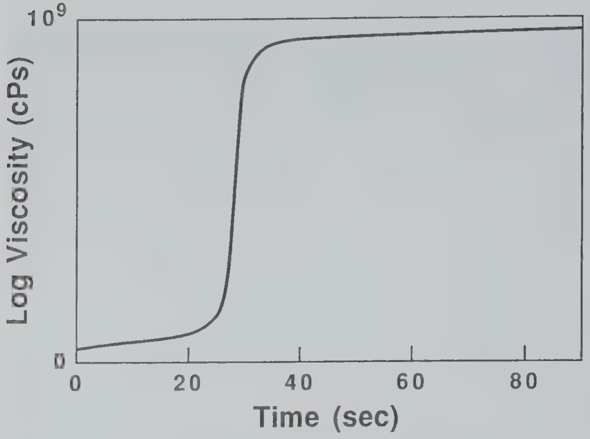

Figure 6. The viscosity—cure behavior of a typical S-RIM resin.

The low viscosity of S-RIM resins and their relatively long mold fill times are crucial in allowing them to penetrate and flow through their reinforcing preforms. If the viscosity is too low (<30 cPs), the turbulent flow in the mold cavity can entrap air and create voids in the composite. However, some turbulent flow through the reinforcement mats is desirable, since it serves as an after-mixing process leading to a more homogeneous cure. Excessive resin viscosity can retard flow through the preform, leading to resin "racetracking," large voids/dry spots and/or distortions in the preforms. Table 1 summarizes some of the processing characteristics of current commercial S-RIM resins. Neat resins and their composite properties are given in tables 2 and 3, respectively. The following sections briefly summarize the S-RIM activities of American chemical companies.

3.1 Amoco Chemical Company

Amoco has traditionally supplied chemical intermediates and polyester resin components to the reinforced plastics/composites market. In recent years, they have been promoting polyester/polyurethane hybrids and have entered the retail resin market with a product called XYCON® [21–23].

While developed primarily as an RTM or a sheet molding compound (SMC) resin, it has been used experimentally in S-RIM moldings [24–26]. These hybrid resins are formed by combining an isocyanate plus catalyst (side A) with an unsaturated polyester/polyol diluted with reactive styrene plus catalyst and additives (side B). During cure, the isocyanate reacts with the polyester polyol to produce a linear molecule with a high molecular weight. The styrene reacts with the unsaturated portion of the polyol to provide stiffness and strength through a network of crosslinks [21]. There have been no reported commercial S-RIM applications of XYCON®.

3.2 Arco Chemical Company

ARCO entered the S-RIM resin market in early 1988 with a product called ARSET® [27]. It is based on a two-component carbonate/polyol modified polyisocyanurate/oxazolidone. The A side of the resin is an isocyanate and may be a carbodiimide-modified MDI (4-4′-diphenylmethane diisocyanate), a glycol-modified MDI or a polymeric MDI. The B side is a proprietary catalyzed carbonate/polyol blend with a viscosity of <10 cPs at 25 °C [28].

ARCO currently offers three grades of ARSET® [29]:

- LV 3100
  This is a low-viscosity resin system for S-RIM applications requiring high fiber loadings and high temperature stability.
- HI 2800
  This is a fully formulated resin system designed for energy management applications below 250 °F.
- HT 3500
  This is a resin system designed for applications where energy management and long-term temperature resistance is critical.

  To date no commercial sales of ARSET® parts have been reported, but developmental prototype moldings are apparently underway [30].

3.3 Ashland Chemical Company

The term "S-RIM" was coined by Ashland, who pioneered its application in the United States in 1985. The first commercial S-RIM molding, a spare tire cover molded by Ardyne Inc., initially used an Ashland AIRMAX® resin [31].

In late 1988, Ashland was reported as trying to sell its AIRMAX® RIM division, but no sale has been publicly announced [32]. A recent publication has claimed that Ashland is not seeking new applications for AIRMAX® but is concentrating on current customers [33].

The AIRMAX® system is based upon the reaction of an isocyanate and a monomer identified by

Table 1. Processing characteristics of commercialized (non-foamed) S-RIM resins[a]

Company	Resin	Mix Ratio[b] (Isocyanurate/ polyol)	Viscosity (cPs)		Component Temp. (°C)		Molding Temp. (°C)	Impingement Pressure (psi)	Injection Rate (lb/sec)	In-Mold-Gel Time (sec)	Cure Time (sec)
			A side	B side	A Side	B Side					
ARCO	ARSET® LV3100	2.3/1.0	35	7 to 20	24 to 38	32 to 43	21 to 66	500 to 2000	0.5 to >5	5 to 300	10 to 300+
	ARSET® H2800	1.5/1.0	60	35	24 to 38	32 to 43	49 to 66	500 to 2000	0.5 to >2.5	5 to 60	10 to 40+
	ARSET® HT3500	2.3/1.0	50	35	27 to 38	29 to 41	49 to 66	500 to 2000	0.5 to >5	5 to 60	10 to 40+
ASHLAND	AIRMAX® 1100	1/2 (Iso/AIRMAX)	≈50	500	20 to 60	20 to 60	80 to 110	1800 to 2000	0.3 to >7	1 to 20	45 to 90
BASF	ELASTOLIT® SR 300	.98/1.0	--	--	--	--	≈66	--	--	--	120 to 180
DOW	SPECTRIM® MM310	1.2./1.0	180	250	27 to 32	43 to 49	54 to 66	1000 to 1500	0.5 to 2.0	10 to 2	45
	SPECTRIM® MM354	2.4/1.0	50	80	29	24	88 to 99	1000 to 1500	0.5 to 2.0	8	45
	SPECTRIM® MM373	2.0/1.0	50	84	27	27	93 to 99	1000 to 1500	0.5 to 2.0	10	60
GOODRICH	TELENE®	45/55 to 55/45 (A/B)	100	100	23	23	60 to 80	500 to 1500	0.5 to 10	10 to 300	20 to 300
HERCULES	METTON® 5000	1/1 (A/B)	≈100	≈100	30 to 35	30 to 35	60 to 90	500 to 1500	0.5 to 10	10 to 30	20 to 120
ICI AMERICAS	RIMLINE® GMR	1.44/1.0	300	1200	29 to 32	29 to 32	54	2000	0.5 to >5	20 to 80	120 to 300
MOBAY	BAYDUR® STR 400	2.17/1.0	40	50	32	32	65	500 to 2500	0.3 to 2.0	5 to 180	15 to 540

[a] As reported by each company.

[b] The AIRMAX® 1100 TELENE®, and METTON® resins are not Isocyanurate/Polyol systems and the ratios are by weight.

Table 2. Neat resin properties of commercialized (non-foamed) S-RIM resins[a]

Company	Resin	Specific Gravity (gms/cc)	Tensile Strength, 10^3 (psi)	Tensile Modulus, 10^3 (psi)	Tensile Elongation (%)	Flexural Strength, 10^3 (psi)	Flexural Modulus, 10^3 (psi)	Izod Impact, Notched (ft-lb/in)	HDT@ 264 psi (°C)	Shore D Hardness	Shrinkage (%)
ARCO	ARSET® LV3100	1.23	7	290	3.5	12	310	0.3	149	84	2.2
	ARSET® H2800	1.23	7	320	12	10	280	0.3	82	79	1.35
	ARSET® HT3500	1.27	9	380	3.4	13	350	0.4	120	84	1.51
DOW	SPECTRIM® MM310	1.19	6.8	--	19	10.6	266	--	--	--	0.8
	SPECTRIM® MM354	1.25	10.2	--	6.0	16.3	401	0.7	119	--	--
	SPECTRIM® MM373	1.25	9.0	--	7.0	16.0	420	0.5	194	--	1.5 to 1.7
GOODRICH	TELENE®	1.03	6.5	267	>6.5	9.8	260	9	110	--	--
HERCULES	METTON® 5000	1.03	6.9	--	70	9.0	270	8	97	--	1.5
ICI AMERICAS	RIMLINE® GMR	1.24	9.0	--	9.0	--	310	0.5	150	--	--
MOBAY	BAYDUR® STR 400	1.22	5.5	--	7.0	--	395	1.8	--	--	--

[a] As reported by each company.

Table 3. Typical composite properties of commercialized (non-foamed) S-RIM resins[a]

Company	Resin	Glass Content (wt%)	Specific Gravity (gms/cc)	Tensile Strength, 10^3 (psi)	Tensile Modulus, 10^3 (psi)	Tensile Elongation (psi)	Flexural Modulus, 10^3 (psi)	Flexural Strength, 10^3 (psi)	Izod Impact, Notched (ft-lb/in)	HDT @ 264 psi (°C)
ARCO	ARSET® LV3100	22	1.32	10	790	2.6	725	19	9.1	210
		46	1.56	24	1500	2.3	1300	35	17.2	249
	ARSET® H2800	22	1.36	13	780	2.5	650	20	8	185
		47	1.55	29	1400	2.4	1310	35	18	210
	ARSET® HT3500	22	1.36	11	835	2.5	730	20	9	204
		47	1.56	26	1560	2.1	1420	42	17	230
ASHLAND	AIRMAX® 1000 SERIES	30	1.40	16.6	1100	2.1	1030	26.9	11.2	240
		40	1.46	18.1	1260	2.1	1060	33.5	14.8	240
BASF	ELASTOLIT® SR 300	10	1.17	10.0	--	--	500	--	8.5	--
DOW	SPECTRIM® MM310	29	1.39	17	975	2.3	730	25	9.4	191
		45	1.59	30	1555	2.5	1250	40	14.1	207
	SPECTRIM® MM354	25	1.42	17.5	--	--	882	27.9	7.7	214
		35	1.51	20.9	--	--	1161	27.0	9.1	228
	SPECTRIM® MM373	25	1.42	14.9	--	6.5	950	28.1	7.0	216
		28	1.54	21.0	--	--	1250	36.7	9.5	232
GOODRICH	TELENE®	18	1.14	8.5	--	20	500	--	16	132
HERCULES	METTON® 5000	28	1.24	10.0	670	2.5	700	--	15	130
ICI AMERICAS	RIMLINE® GMR	25	1.38	13.0	--	3.0	720	--	9.0	>250
		38	1.49	22.0	--	2.2	1085	--	15.0	>280
MOBAY	BAYDUR® STR 400	49	1.60	28.0	1600	<2.0	1500	41.0	14.0	190

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[a] Reinforced with random-glass mat.

Ashland as an acrylesterol. The resulting polymer is termed an "acrylamate" [34–36]. In 1987 Ashland expanded their AIRMAX® family to include a triazathane/isocyanate polymer.

Ashland currently offers three grades of AIRMAX® [37]:

- AIRMAX® 1100 and 1150
  This resin system is designed for high temperature and structurally demanding applications.
- AIRMAX® 1500
  This resin has lower temperature resistance than the AIRMAX® 1100 series but improved tensile and flexural properties.
- AIRMAX® 2100
  The triazathane chemistry used in this resin has higher elongation and toughness than the acrylamate polymers used in the other members of the AIRMAX® family.

The AIRMAX® resins have been used commercially in tire covers, a satellite dish, a copier heat shield, and an automotive underbody sound shield. Prototype activities are extensive and reportedly include an automotive structural floor pan, components of recreational vehicles and parts of agricultural vehicles.

3.4 BASF Corporation

BASF Corporation's Chemicals Division entered the S-RIM resin market in late 1988 with a polyurethane/polyisocyanurate-based resin called ELASTOLIT® SR. This resin system is available in three grades [38]:

- ELASTOLIT® SR 100
  This resin is designed for foamed S-RIM applications, and it uses freon and freon substitutes (except water) as blowing agents.
- ELASTOLIT® SR 200
  This resin is similar to the SR 100 resin except that it uses water as a blowing agent.
- ELASTOLIT® SR 300
  This resin is designed for conventional high-density (i.e., non-foamed) S-RIM applications.

The ELASTOLIT® resins are reportedly undergoing evaluation trials in 1990 at several molders. No production applications have been announced.

3.5 Dow Chemical Company

In recent years Dow has become the major supplier of S-RIM resins in the United States [39]. Their SPECTRIM® MM family of polymers has become widely used in many applications [40–44]. This family of resins consists of two types of polyisocyanurates and a polycarbamate [45]:

- SPECTRIM® MM 310
  This resin is a three-component, fast-reacting, low-viscosity polycarbamate for applications requiring toughness and good impact properties. It is not recommended for long-term exposures above 225 °F (107 °C).
- SPECTRIM® MM 354
  This resin is a two-component, low-viscosity polyisocyanurate especially formulated for large surface area parts requiring long flow distances.
- SPECTRIM® MM 373
  MM 373 is similar to MM 354 except that it has a much shorter gel time.

The SPECTRIM® resins are currently being used commercially in spare tire covers and a structural bumper beam. Trade reports have suggested that these resins are being evaluated in numerous prototype structural bumper beams, structural instrument panels, automotive knee bolsters, and a pick-up box.

3.6 BF Goodrich Company

Goodrich's Specialty Polymer and Chemical Division has reportedly commercialized a norbornene dicyclopentadiene (DCPD) resin under the trade name TELENE®—RIM [46–47]. The reaction forming this polymer is based upon metathesis chemistry, which in this case is a chemical reaction where two reactants become united through a ring-opening mechanism with one another usually under the influence of an organometallic catalyst [48]. Goodrich has marketed three grades of TELENE®—RIM [49]:

- TELENE® Standard Formulation
  This formulation is designed for conventional RIM or RTM equipment and possesses a balanced combination of stiffness, impact strength and heat deflection temperature.

- TELENE® Fiber Glass Reinforced Glass Mat
  This variant of the standard TELENE® formulation is designed for glass fiber reinforced applications like S-RIM.
- TELENE® Flame Retarded
  This resin is formulated for applications requiring good flammability resistance without sacrificing stiffness and impact strength.

While developed primarily for RIM applications, TELENE® has reportedly been tried in S-RIM parts [46]. However, no commercial S-RIM applications have been announced publicly.

3.7 Hercules, Inc.

Hercules entered the DCPD market in April 1985 with a family of resins sold under the trade name METTON® [46,50–53]. These resins use a metathesis catalyst to polymerize DCPD via a RIM process [54]. Currently, Hercules markets METTON® in two major families [55]:

- METTON® M1000 Series
  This family of DCPD resins is designed for RIM applications where impact strength, surface appearance and dimensional stability are critical.
- METTON® M5000 Series
  This low-viscosity DCPD resin series is designed to maximize fiber wet-out, provide acceptable surface finish, and be compatible with S-RIM processing conditions.

The METTON® resins have captured all publicly announced DCPD RIM applications. They have been used commercially in snowmobile hoods, watercycle hoods, golf cart components, automotive bumpers, and dunnage applications. Trade reports have identified METTON® as the resin used in a major U.S. automotive company's prototype S-RIM truck hood program. The reinforcing glass mat in this hood is placed only in high-stress locations, resulting in a "Class A" surface elsewhere [46]. Hercules has required that METTON® molders be licensed, and at least six companies in North America are currently using it [56].

3.8 ICI Americas, Inc.

ICI introduced two polyurethane-based S-RIM resins in late 1987. The chemistry of these resins appears to be a classical polyol/isocyanurate polymerization. ICI uses a proprietary catalyst system to obtain a snap cure with extended adiabatic gel times of more than 1 minute [57]. These resins are named RIMLINE® and two systems are available [58–59]:

- RIMLINE® GMR-200
  This resin is formulated with a blowing agent and is designed to make 20% to 30% (by weight) fiberglass S-RIM foamed articles. The molding temperature of this resin, 130 °F (54 °C), is about 70 °F (21 °C) lower than most other S-RIM resins.
- RIMLINE® GMR-5000
  This resin has been formulated for the production of high-fiber-content, high-strength composites. Good durability in hot air and hot oil environments has been reported [57].

The GMR-200 system has been evaluated in decklid spoilers, internal sunvisors for trucks and vans, and business machine enclosures. The GMR-5000 system is used commercially in a telescoping pickup truck cargo area cover.

3.9 Mobay Corporation

Mobay is the commercial leader of polyurethane resins for RIM and RRIM (Reinforced RIM) applications in the United States. In late 1986, Mobay introduced two S-RIM polyurethane resins: S-RIM 250 and S-RIM 400 [53,60-61]. Currently, S-RIM 300 and S-RIM 400 are marketed by Mobay [61] under the Baydur® trade name:

- Baydur® STR/F 300
  This formulation of STR 300 is a water blown, foamed resin for making low-density S-RIM parts.
- Baydur® STR 400
  This resin has a low-viscosity, two-component system with adjustable gel times of 10 to 22 seconds and cure times of 30 to 90 seconds. It can be formulated with a blowing agent to produce a structural S-RIM foam.

Mobay has an S-RIM Internal Mold Release resin system under active development for STR 400.

A foamed Mobay S-RIM resin system has been used to make door panels and other interior automotive parts commercially [33]. Prototypes of automotive roof sections, bumper beams, instrument panel retainers, and a structural floor pan have shown by Mobay at trade shows. An S-RIM composite satellite antenna and an office chair seat/back structural shell have recently been commercialized using Mobay's S-RIM resins.

3.10 Owens-Corning Fiberglas Corporation

While known primarily for its fiberglass products, Owens-Corning Fiberglas (OCF) developed and field tested an unsaturated, isocyanate-based S-RIM resin in 1987 [64]. Good processing characteristics and excellent properties were reported, but this resin was never commercialized [65].

4. S-RIM Processing Technology

The equipment and processing techniques used by S-RIM have largely evolved from those developed for RIM/RRIM and RTM except for those related to preforming, which tend to be unique to S-RIM. As illustrated in figure 7, S-RIM does occupy a slightly different molding window from those occupied by either RIM/RRIM or RTM.

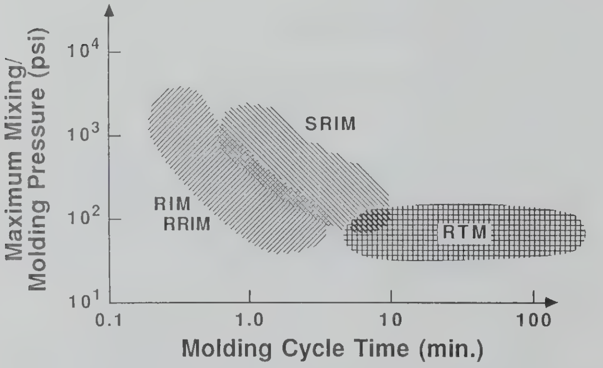

Figure 7. Molding pressure and cycle time domains for RIM/RIM, RTM and S-RIM.

4.1 Equipment

The increased use of S-RIM can, in part, be attributed to the fact that most RIM/RRIM equipment can also be used in S-RIM. However, high-volume S-RIM applications usually involve the development of more specialized molding equipment.

Sources for complete RIM/RRIM/S-RIM systems include Admiral Equipment, BASF/Elastogran Machinery, Battenfield of America, Cannon USA, Cincinnati Milacron, Krauss-Maffei, Mobay Machinery, and Perros (EFY Corporation) [33]. In Europe Elastogran Gmb H, Impianti, Klockner Ferromatic Desma, and Plastech TT are supplying similar equipment [66]. A growing trend in RIM/RRIM/S-RIM equipment is modularization. Using this approach, the equipment builder constructs a unique S-RIM unit composed of individual modules which meets the requirements of the customer. These modules can be replaced with enhanced units as the needs of the molder change or as technology advances.

A schematic of a typical S-RIM molding equipment configuration is given in figure 1. S-RIM molding equipment is composed of two equivalent sets of mechanical components for handling the reactive "A" and "B" sides of S-RIM resins. The individual resin components are stored in tanks under a positive pressure usually provided by a dried, inert gas. The resin is then drawn through filters to remove any contaminants that might clog the fine orifices of a downstream mix head.

Impingement pressure for the resin components in the mix head is provided by axial piston pumps or lance cylinders. The mix head mounted to the outside of one cavity of the compression mold provides the injection/mixing action which initiates the polymerization reaction and fills the cavity of the mold with the proper amount of reacting resin. When the mix head is not injecting resin into the mold in its high pressure mode, it recirculates the "A" and "B" reactive resin components back into their holding tanks. Usually most RIM injection units also have a low pressure mode in which the recirculating "A" and "B" components bypass the mix head.

A heat exchanger is used by each side of the S-RIM equipment to regulate the temperature of the resin components. Usually, optimum property and processing results can be achieved by maintaining the resin component temperatures at or slightly above ambient room temperature (23 °C). Since the resin travels through fine orifices in the S-RIM mix head during its recirculating path and this mix head is mounted on a heated mold cavity, the resin components can quickly become hotter than desired and the heat exchanger generally functions as a cooling device. The following paragraphs in this section provide more details about S-RIM metering equipment, S-RIM mix heads, and S-RIM clamps.

4.1.1 S-RIM Metering Equipment The metering unit in RIM/RRIM/S-RIM is responsible for the delivery of controlled ratios at high volume and high pressures of the low-viscosity reacting resin streams. Axial piston pumps used in RIM are commonly employed in S-RIM operations. Ardyne Inc. (a leading S-RIM molder) uses customized axial piston pumps (fig. 8) in the manufacture of S-RIM tire covers and the Corvette front bumper beam [33].

In many RRIM applications, axial piston pumps have been replaced with metering lance cylinders. Several S-RIM equipment manufacturers now offer metering cylinders on their S-RIM systems. Cannon's model HE S-RIM metering unit incorporates variable output capability with closed loop control on injection pressure during the length of the shot [67].

S-RIM processing can require large shot capacity with typical shot times of 5 to 30 seconds at output ranges from 0.2 to 4 lbs/sec. The advantage of an axial pumping unit is that the shot capacity is only a function of the machine output rate, whereas with a lance cylinder it is a function of the capacity of the cylinder [68,69]. However, a lance cylinder offers better accuracy and better ability to control and record process parameters.

Since S-RIM metering units are, at most, slightly modified RIM metering units which are designed around handling polyurethane, S-RIM molders generally have "made do" with this commercial equipment by modifying it to handle S-RIM resins, which often process significantly different from polyurethanes. These modifications can include line heat-tracing to maintain higher circulating temperatures, pump modifications to handle "A" and "B" resin streams of differing pressures, and extra tanks for multiple-component resins.

4.1.2 Mixing Heads Of all of the technology that goes into S-RIM equipment, the design and operation of mixing heads tend to be the most proprietary. The processing of S-RIM polymers depends critically upon the proper mixing and flow distribution of the "A" and "B" resin streams throughout a part. Hence, the use of a self-cleaning mix head with variable injection pressure capability is the key piece of equipment in the S-RIM molding process.

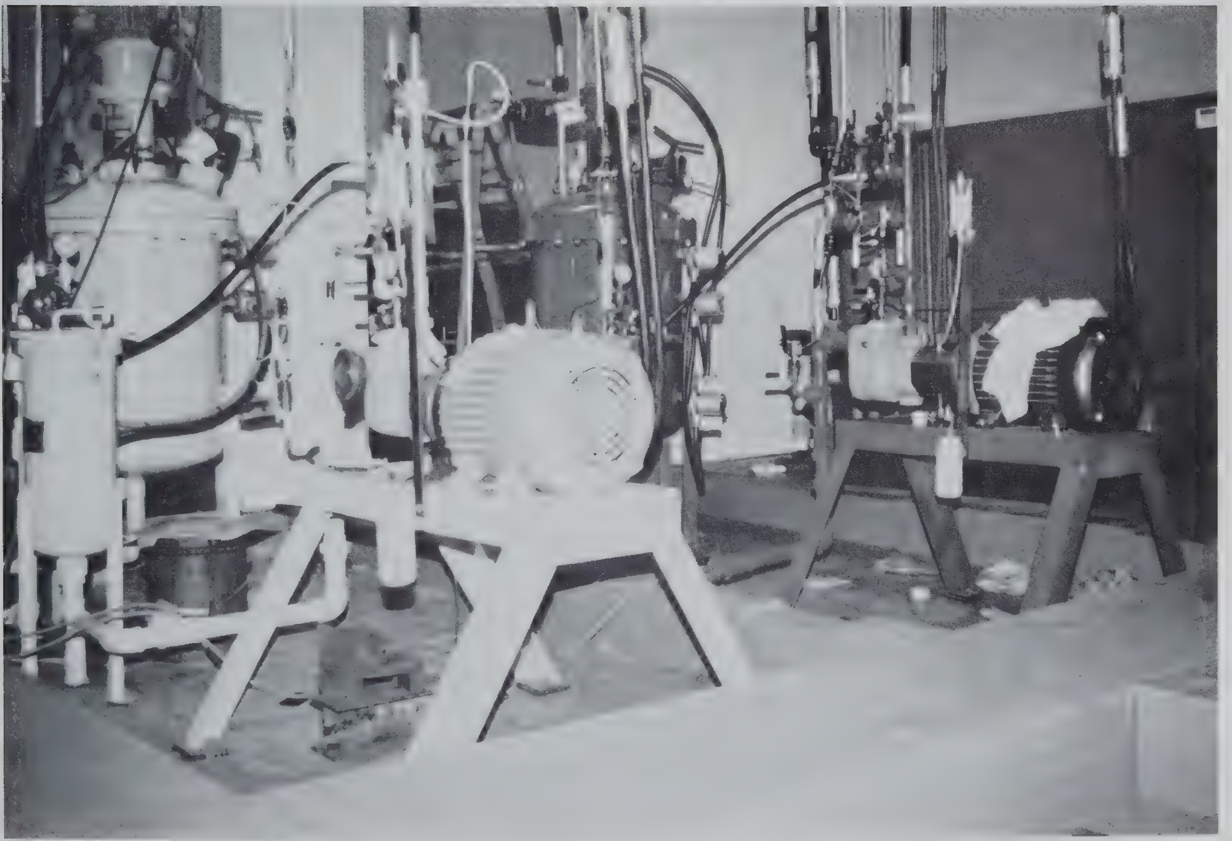

Figure 8. Automated S-RIM metering system (courtesy of Ardyne, Inc.).

As in the case of metering equipment, mix heads were originally designed for RIM-based polyurethanes. These mix heads contain a mixing chamber where various mechanical mechanisms have been used which rapidly open and close the high-pressure direct, head-on impinging "A" and "B" resin streams. This high-pressure, turbulent mixing is the process which allows S-RIM polymers to react rapidly. The fluid pressure from the incoming resin streams sweeps the mixing reacting resin, now at greatly reduced pressure, into the mold cavity containing the preform. Further turbulent flow through the reinforcing fibers of the preform serves as an after-mixing process. Usually a piston is used to clean out the mixing chamber after injection to prevent cross-feeding of the resin streams A cross-sectional illustration and a photograph of a mix head are shown in figures 9 and 10, respectively.

Mix heads are generally bolted to the molds which they serve. The mixing chamber itself, however, may be just inside the mold. Mobay Machinery uses such a design. Several equipment manufacturers now offer a microprocessor-controlled, self-adjusting mix head that maintains mixing pressures over a wide range of injecting nozzle openings [59,67].

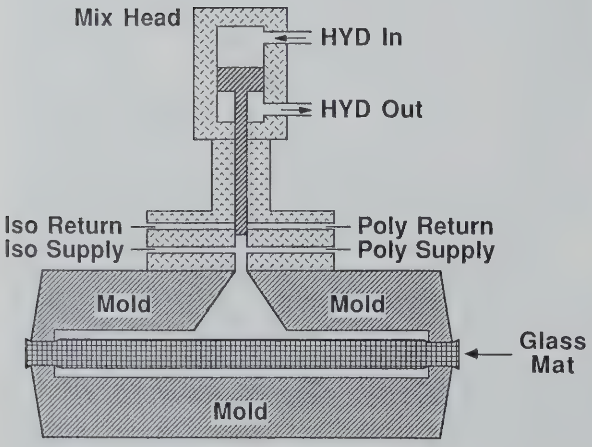

Figure 9. A cross-sectional illustration of a RIM mix head.

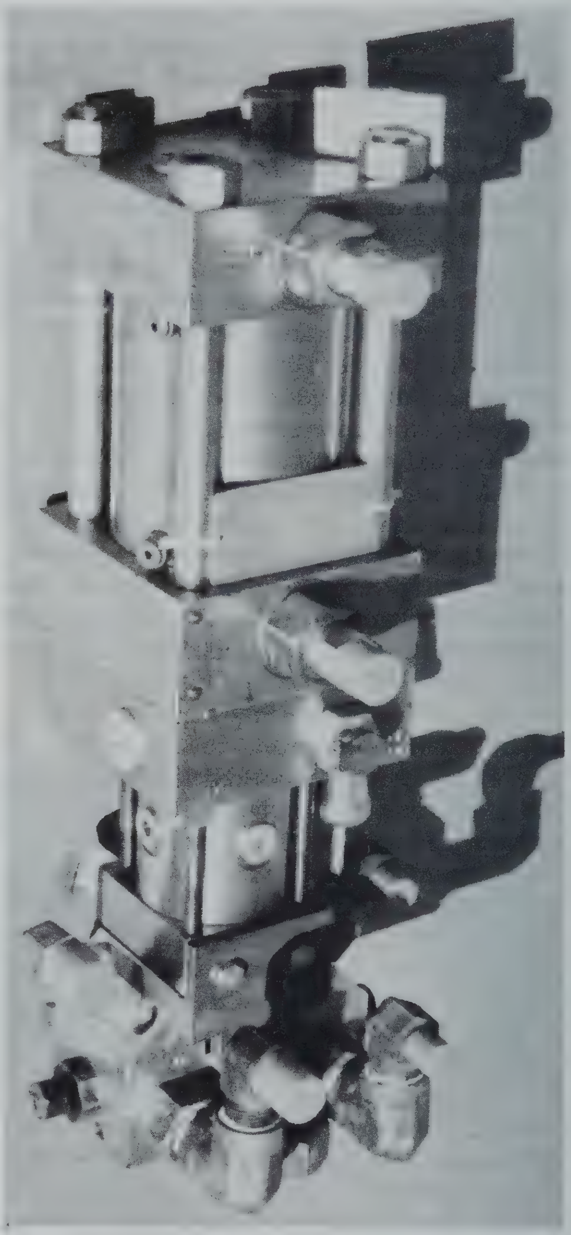

Figure 10. A photograph of a RIM mix head.

To minimize preform washing and distortion, it is possible to use profiled resin injection pressure units. In this equipment, adjustable needle valves allow for low pressure at the start of injection which is subsequently ramped up during injection. Battenfield, Cannon, Krauss-Maffei, and Perros offer various types of profiled resin injection mix heads [33].

4.1.3 Clamps As with metering equipment and mixing heads, S-RIM clamps were adapted from RRIM/RIM units and are currently following similar trends. Many types of clamping systems have been used by S-RIM molders. The current movement is toward higher tonnages, as much as 600 tons, to minimize flash [33]. Still, these clamp pressures are modest when compared with injection molding or SMC equipment (about 4,000 tons). While the impingment pressure of S-RIM can approach 1000 psi (fig. 7), the clamping force necessary to keep the mold halves of an S-RIM tool together during molding is usually less than 100 psi.

There are two types of clamps used in S-RIM molding: vertically acting and horizontally acting. Vertically acting clamps are by far the more common. Usually, vertically acting S-RIM clamps incorporate a "booking" motion into their operation. This action allows the upper and/or lower mold platens to book open at angles approaching 90° [68]. The mold operator thus has ease of access to the interior mold surfaces for cleaning and for removal of parts.

Horizontally acting clamps with a vertically tilting motion have been developed by PPD Industries, Inc., of Canada for molding DCPD resins. These clamps have 6 foot × 10 foot platens capable of molding parts weighing up to 100 pounds [70]. In addition to some of the S-RIM equipment suppliers mentioned in section 4, presses suitable for S-RIM are sold by Drake, John T. Hepburn, Tyler Machinery, and Wabash Metal Products.

A recent development in S-RIM clamps which differs significantly from that of RIM/RRIM clamps is the construction of vertically acting shuttle bed presses. These presses avoid the payment of a severe cycle-time penalty for the dead time in S-RIM molding which occurs during the placement of a preform in the mold cavity [71].

In an S-RIM shuttle press, one half of the mold (usually the lower half) is duplicated. Each of these duplicates is affixed to a bed which shuttles into position underneath the press while the other duplicate mold is being prepared for its next cycle. Battenfield has delivered a small shuttle-bed press to a materials laboratory [72], and Cannon USA has built a 600-ton system for Mobay Chemical and a 450-ton unit for Carino Concepts/ Decoma (a division of Magna) in Canada [33]. Figure 11 is a photograph of a Cannon Shuttle Bed Press. Other S-RIM equipment suppliers have reportedly designed similar units.

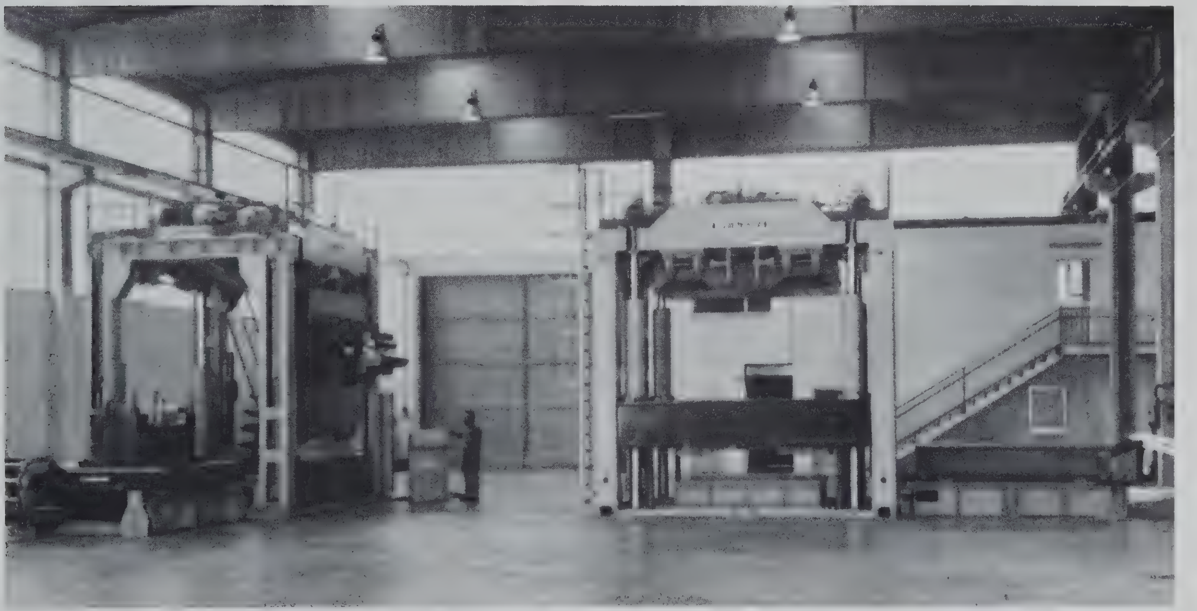

Figure 11. A photograph of a S-RIM shuttle bed press (courtesy of Cannon USA, Inc.)

4.2 Molding

Once the resin has been mixed, the overriding processing concerns are filling out the mold and wetting the reinforcing preform without distorting it, all in a matter of seconds. The design of S-RIM molds, their composition and the techniques used to insure complete mold filling are critical components in completing the S-RIM molding process.

4.2.1 S-RIM Molds As S-RIM parts have gotten more complex in the last 5 years, their molds have become more complicated. S-RIM prototype parts which apparently were molded with moving slides and ejector pins have been shown recently at trade shows. While used extensively in thermoplastic injection molds, the very low viscosities of hot, reacting S-RIM resins makes sealing these moving slides and ejectors in S-RIM molds a major challenge. In addition, the glass reinforcement used in most S-RIM preforms is very abrasive and can cause peening of the sealing surfaces of a mold. Eventually, fiberglass containing flash (which stoutly resists trimming) will form in these areas [33].

Most high-volume S-RIM applications have used steel molds. With the trend in many industries toward more frequent part design changes and subsequently shorter production runs per mold, a slow shift to non-steel mold materials is underway. The low pressures encountered in S-RIM molding are encouraging this movement. Even so, some molders suggest that S-RIM production volumes in excess of 10,000 parts should still be molded in steel tools depending upon the nature of the part being molded [33].

The chief alternatives to tool steels [73] for use in making S-RIM molds are:

- Castable "steel-like" alloys [74];
- Kirksite (an alloy of aluminum, copper, zinc, and traces of other metals);
- Chemically bonded ceramics [75];
- Cast and machined aluminum;
- Epoxy (with [76] and without [77] nickel shells)
- Sprayed metal [78].

Table 4 is a comparison of these materials for use in S-RIM molds.

Kirksite, chemically bonded ceramics, and epoxy tools generally are less expensive than the other tool materials mentioned above. However, these materials' poor thermal conductivity usually bars their use in high-production S-RIM runs where a rapid resin heat-up rate is desired to minimize cycle time. In prototype part applications, this is usually not a significant factor, and these materials are widely employed [33,77].

4.2.2 S-RIM Mold Filling Filling the mold cavity in S-RIM processing occurs rapidly. Generally it is measured in seconds even for parts with high glass loadings [80]. To assist in directing the flow of resin into the preform of large S-RIM parts, runners are often machined into the surface of a mold.

Since the resin will find the path of least resistance as it flows through a mold cavity packed

Table 4. Materials for use in S-RIM molds

Tool Material	Percent of Equivalent Injection Molding Tool Costs[a]	S-RIM Use
Machined Mold Steel	80–100	Production
Machined Aluminum	60–80	Production
Castable "Steel-like" Alloys	50–70	Production
Kirksite Tooling	45–65	Limited Production, Prototype
Cast Aluminum	35–55	Limited Production, Prototype
Chemically Bonded Ceramic	30–50	Very Limited Production, Prototype
Sprayed Metal	25–45	Very Limited Production, Prototype
Nickel Shell Epoxy	25–35	Very Limited Production, Prototype
Epoxy	15–30	Prototype

[a] Reference 79 was the source for most of these estimates.

with a preform, very circuitous resin flow routes often occur during S-RIM mold filling. The placement of varying density preforms, anisotropic preforms and/or impervious inserts in a complex, three-dimensional mold cavity can lead to resin "race tracking." This causes dry spots in the preforms and, when cured, these are major S-RIM molding defects.

Design of the gating and runner configuration (if any) is usually kept proprietary by the molder. However, it would appear that most S-RIM parts are center gated with vents located along the periphery of the part. This configuration allows for the displaced air in the mold cavity to be expelled uniformly. Deviations from this approach are likely used by molders only when they encounter problems with race tracking or poor mold filling. These mold modifications are usually based upon the experience of the molder and "trial-and-error" experimentation.

Some researchers in the past few years have been trying to bring technology to bear on this art. Measurements of preform permeabilities [81] and pressures [82] in S-RIM molding have provided a data base to use for estimating resin flow in S-RIM tools. Using Darcy's Law, several investigators have simulated two-dimensional S-RIM fluid flow and compared their calculated results with laboratory experiments [83–85]. While their results have been very promising, much more work will be required before this computational technique can be fully developed as a tool to aid in S-RIM mold design.

Some molders have used the RTM technique of sealing the edges of a tool and pulling a vacuum through the vent ports as an aid in filling out S-RIM molds. Others have found that this procedure only encourages race tracking [33]. Recently detailed observations of S-RIM mold evacuation have demonstrated that this procedure decreases the size of entrapped air bubbles during molding but ultimately increases the maximum pressure during fill [84]. Similar studies measuring the permeability of continuous strand mats, unidirectional mats and bidirectional mats, in multiple layers have provided insights into synergistic flow effects that can be used to optimize mold fill-out [85].

Understanding these phenomena becomes more important as S-RIM parts become larger and more complex in shape and when the fiberglass volume fraction approaches 30%. Eventually a point is reached where injection through a single port cannot fill the mold before the resin gels. The solution to this problem is to use multiple injection ports. These injection ports could be shot either simultaneously or sequentially [86]. Understanding the optimum placement of the injection ports and determining the timing of their injection can be aided through computerized mold filling simulation.

4.3 Automated Manufacturing

The initial commercial success of S-RIM molding was aided by Ardyne Inc.'s development of a semi-automatic manufacturing line to produce spare tire covers [87,88]. The cycle time for this 25% by weight reinforced CSM product now averages one part per minute in a two-cavity mold with a 2.5-second injection time (fig. 12). Upwards of one million parts per year have been produced since 1985. Ardyne uses an "H" arranged manufacturing cell with a centralized resin mixing, pumping and distribution system. The presses are shrouded for ventilation, but the S-RIM plumbing system is located down the leg of each cell for ease of maintenance (fig. 13).

Overhead of the manufacturing cell is a centralized closed-loop computer control, monitoring, and SPC control room whose equipment was designed and developed by Ardyne. This system takes decisions on such matters as mixing, the pumping of fluids, and temperature totally out of the press operator's hands [80]. The computer also tracks a complete system diagnostics for each press. Using this automated equipment, Ardyne has kept its scrap rate below 1% [87] while improving productivity by approximately 80% since 1985 [88].

The key to further commercialization of S-RIM lies in adopting currently available technology from other industries to automate the S-RIM process even more. In addition to the automated preform equipment (described in sec. 2) and the S-RIM shuttle bed press (discussed in sec. 4.1.3) being commercialized, a fully automated and integrated S-RIM preforming/molding line has been proposed by Krauss-Maffei [33].

Cannon USA has designed an integrated clamping system, metering unit, computer closed-loop control system, and automated mat preform system called the "COMPOTEC" system [67]. This system can be integrated with a shuttle bed press for optimum performance.

Once an S-RIM part is molded, secondary operations such as flash trimming and the removal of cut-outs are often required. S-RIM materials can be machined by drilling, sawing, punching, abrasive

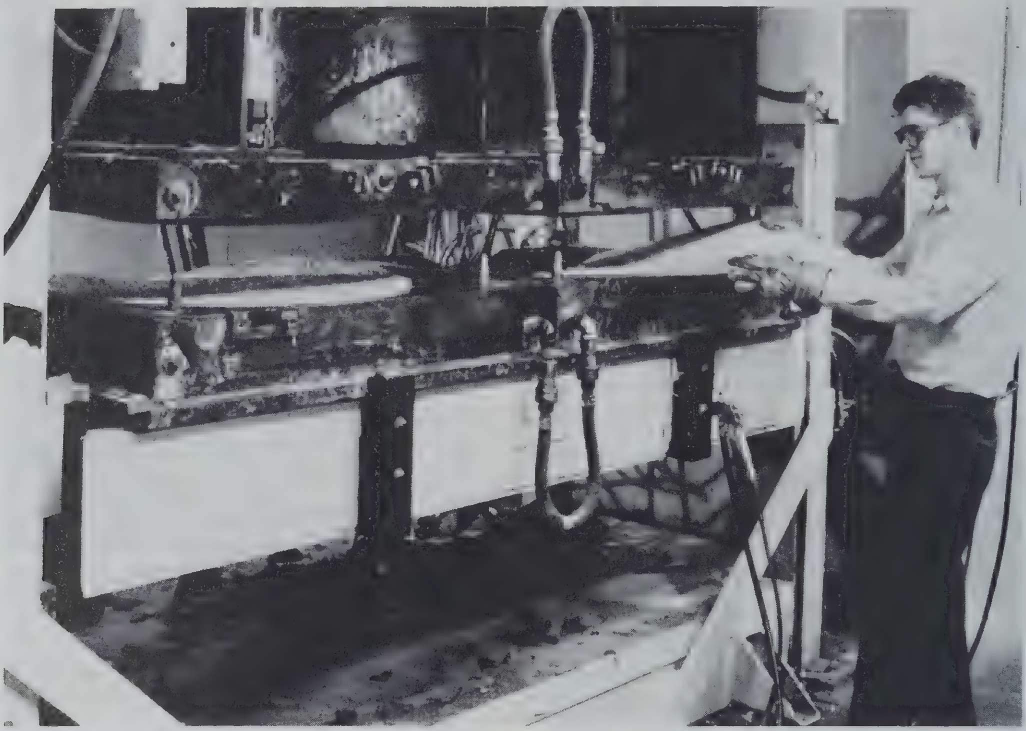

Figure 12. A photograph of a tire cover S-RIM molding clamp (courtesy of Ardyne Inc.).

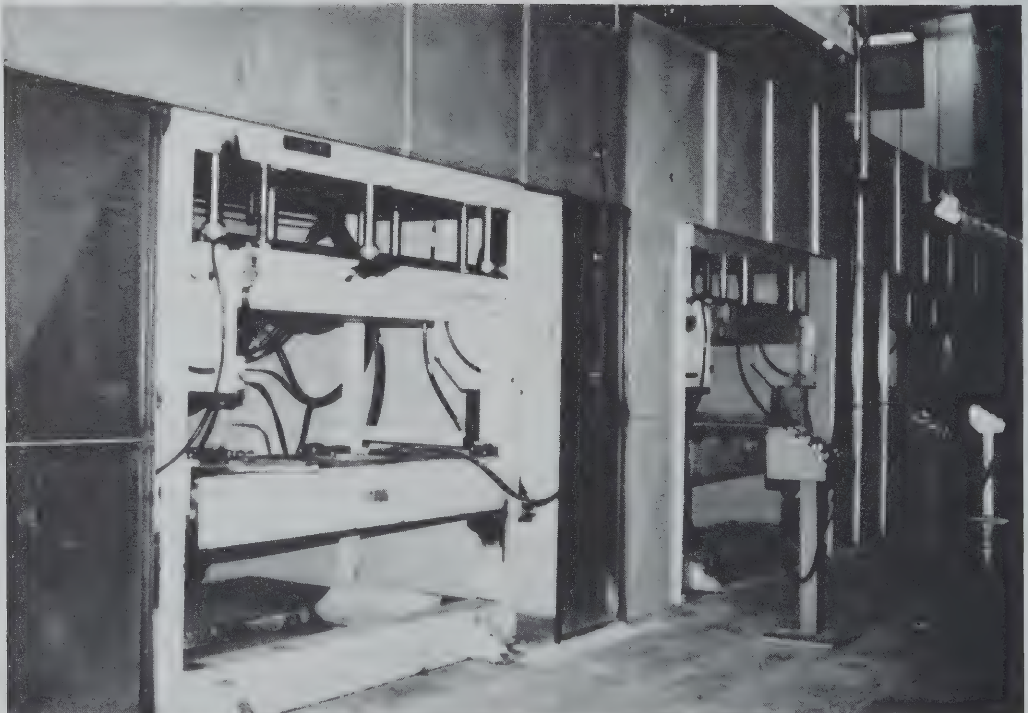

Figure 13. A photograph of the spare tire cover S-RIM molding line (courtesy of Ardyne Inc.).

grinding, routing, and water-jet cutting. Of these, abrasive grinding is perhaps the easiest and fastest. Ardyne's S-RIM spare tire covers are finished with a water-cooled, two-head, six-station CNC router [89]. Water-jet cutting, with multiple-axis control, probably provides the best accuracy and holds the greatest potential for low to medium production volumes. The number and complexity of parts needing trimming governs the degree of automation required.

S-RIM materials handling requirements, particularly for preforms, have not been extensively evaluated. Presumably AGV's, conveyors, and parts handling robots would be appropriate.

4.4 S-RIM Cosmetic Surfaces

S-RIM applications have been limited to noncosmetic parts to date because of S-RIM's poor surface appearance. However, most S-RIM resin suppliers and molders believe that cosmetic S-RIM surfaces are possible, perhaps within 5 years. Limited work to date has focused on hiding the glass fibers (which often "read through" to the surface) and nucleated pinholes in S-RIM by applying either RTM surface veils or a cosmetic surface on top of the S-RIM laminate.

The use of surface veils does draw more resin to the surface of S-RIM parts which improves their appearance. The surface quality, however, falls far short of that needed for cosmetic automotive applications (i.e., Class A). These surface veils are also prone to wrinkle in the tool and to move during resin injection.

Several S-RIM equipment suppliers reportedly have adapted the Sherwin-Williams high-pressure, two-part in-mold urethane coating technology, which has been used to provide Class A surfaces to SMC parts, to S-RIM. In this technique the mold is opened very slightly (2–5 mils) and a low-viscosity urethane coating is injected between the part and the cosmetic surface of the adjacent platen of the mold. The coating then cures using the residual heat in the part and heat from the mold platen. This system should be capable of imparting similar surface quality and UV protection to S-RIM as it does to SMC.

An alternative to injecting a coating into the mold would be to spray a coating onto the cosmetic surface of the mold, place the preform into the mold and then inject the S-RIM matrix resin behind the coating. Judicious selection of the coating could result in a chemical bond between the cured coating and the cured S-RIM matrix resin. Both Futura Coatings [90] and Glidden [91] have developed in-mold S-RIM/RIM spray coatings. The Glidden system incorporates a mold release agent in their coating.

Glidden licensed its technology from Macpherson Research in the U.K., which has been active in RIM coatings for a number of years. Macpherson's system has reportedly been in commercial usage in Europe. Neither Glidden nor Futura has reported any S-RIM cosmetic applications of their in-mold coatings. To date, no commercialized low-profile S-RIM resins intended for cosmetic applications have been introduced.

5. Applications

The first S-RIM part commercially produced was the cover of the spare tire well in the trunk of General Motors' C and H body vehicles (Pontiac Bonneville, Oldsmobile 98 Regency, Oldsmobile Cutlass Supreme Classic, Buick Electra, and Buick LeSabre) (fig. 14). This part was molded by Ardyne Inc., in annual volumes initially of 1 million parts per year and recently between 700,000 and 800,000 parts annually [33,83]. Ardyne also molds a similar tire cover for the E/K vehicle (Oldsmobile Toronado, Buick Riviera, Buick Reatta, and Cadillac Seville) but in much lower volumes. Both of these parts utilize Dow Chemical's SPECTRIM® Resin reinforced with a continuous strand mat [83]. Sterling Engineered Products molds a similar Cadillac spare tire cover using a random-fiber mat with ICI's RIMLINE® GMR-5000 resin [92].

Other S-RIM automotive structural trim applications include foamed door panels, sunshades, instrument panel inserts, and rear-window decks. General Motors' Inland Fisher Guide division uses Mobay's Baydur® LV resin, blown with water and reinforced with continuous strand mat to mold a Cadillac Eldorado interior door panel. This S-RIM part replaces a wood-fiber substrate component and offers better dimensional stability and impact absorption and a 40% weight reduction [92]. Inland has been investigating S-RIM for manufacturing more elaborately shaped interior door panels used in wrap-around interior automotive styling. These parts could incorporate such items as carpet, cloth, armrest, trim, ducts, and electricals into the S-RIM molding process [33].

An S-RIM sunshade was shown by BASF Corporation at the 1989 SAE show in Detroit. This sunshade was molded by Magna International's Atoma Division using an Elastolit® SR urethane resin from BASF. This part incorporated a head-

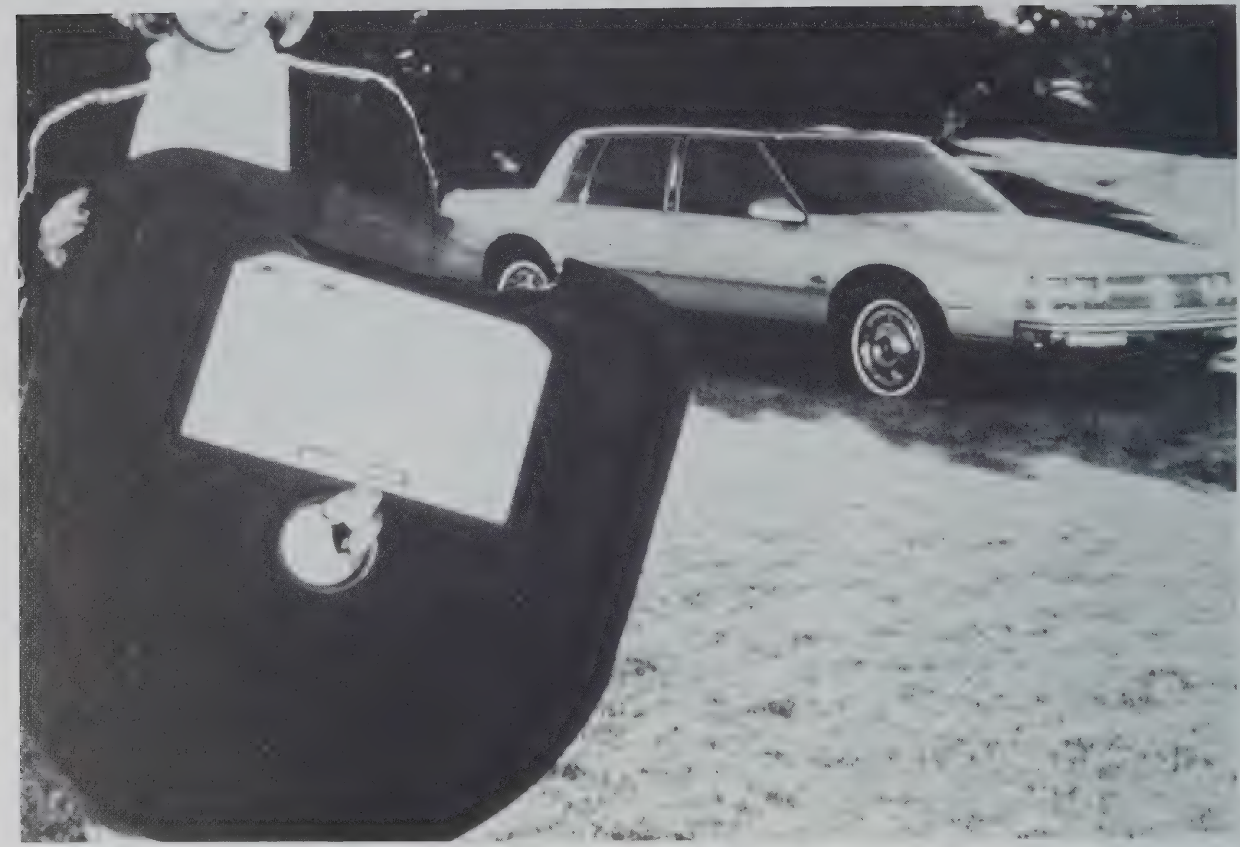

Figure 14. A photograph of a General Motors S-RIM C/H spare tire cover (courtesy of Ardyne Inc.).

liner fabric, an S-RIM reinforcing foam core, and an in-mold coated, grained top surface [93].

Butler Polymet is molding two S-RIM noise shields for Ford diesel trucks. Both parts incorporate about 40% by weight of continuous strand fiberglass mat in an Ashland Airmax® 2100 hybrid resin system [33].

The first commercialized, truly structural S-RIM application was the 1989 Corvette front bumper beam (see fig. 15). This part, molded by Ardyne Inc., is reinforced with 0°/90° woven mats and layers of chopped glass. The glass content ranges from 44% to 53% percent, depending upon location [38,80,92]. The resin system is Dow's SPECTRIM® MM 310 polycarbamate.

S-RIM bumper beams offer reduced weight, lower cost, design flexibility, and part consolidation when compared with alternative materials (SMC, steel, or glass mat reinforced polypropylene). Resin suppliers have recently shown several different S-RIM bumper beams at trade shows [22]. Figure 2 of reference 92 shows four Ardyne S-RIM bumper beams in addition to their Corvette front bumper beam. They have also been quoted as saying that they are working on a total of 10 bumper beams [33]. Thus, it would appear that a plethora of S-RIM bumpers is under development for near-term commercialization.

Not yet in production but under active development by at least two S-RIM molders are composite front-end modules that support the radiator, headlamps, grille, and other attachments between the bumper and engine. Two major U.S. car companies are involved with Decoma Plastics in this type of application [94]. Davidson Technology Center Textron is conducting a similar program to design and construct an integrated S-RIM composite front end of an automobile.

Other automotive S-RIM applications that have been reported include structural instrument panels, roofs, floor pans, a wing-spoiler, and a pick-up box cargo area cover. With the advent of air bags and new federal safety standards for automotive side impacts, instrument panels (IP's) will now be required to carry substantial structural loads. The mechanical properties of the thermoplastic mate-

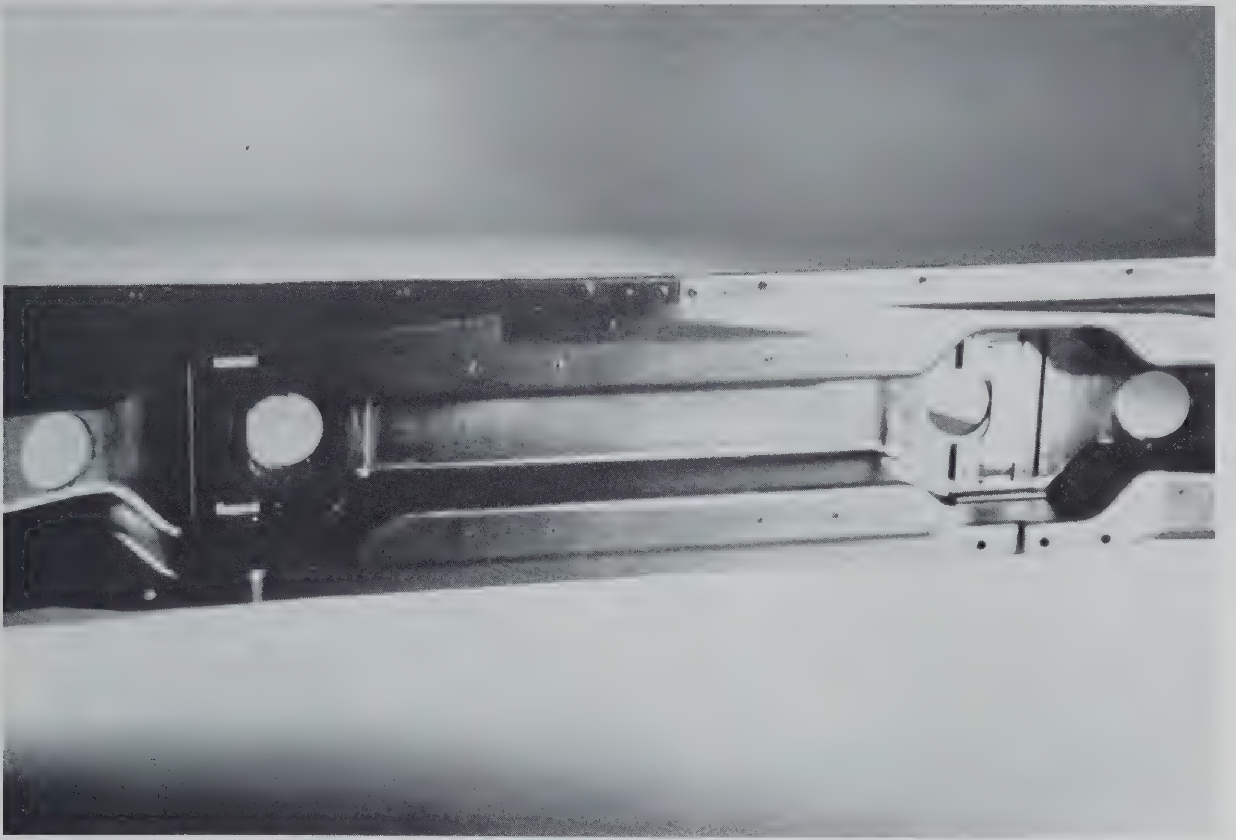

Figure 15. A photograph of a Corvette front S-RIM bumper beam (courtesy of Ardyne Inc.).

rials currently in use in IP's can not meet these requirements. Apparently, both Dow and ARCO have S-RIM structural IP's under development [30].

An S-RIM landau roof for a Chevrolet Monte Carlo was developed by Mobay in 1987 [95,96]. This 11-pound roof contained a 30% by weight glass mat and overall dimensions of 6×3×1.5 ft.

Also in 1987, Carron & Company in conjunction with Ashland Chemical developed a prototype S-RIM floor pan [95, 97]. The floor pan was 0.125 inch thick with a total surface area of 11.8 square feet and weighed 32 pounds. It integrated the bottom, front, and rear passenger bulkheads. The part was molded using continuous strand mat, internal foam cores, and tubular metal reinforcements. A more sophisticated S-RIM floor pan has been shown recently by Mobay at trade shows. To date there have been no announcements of any commercial S-RIM floorpans.

An S-RIM rear aerodynamic spoiler has been jointly developed by specialty supplier Inoue M.T.P. and Mitsubishi for the Galant/Eterna vehicle. This large spoiler weighs 12.1 pounds and is composed of a semi-hard urethane topcoat, a foamed S-RIM layer, and an inner foam core [98].

Two S-RIM pick-up boxes are reportedly under development to compete with the SMC pick-up box recently announced by Ford [99]. Carino Concepts (a subsidiary of Decoma Plastics, a Division of Magna International) has been identified as the molder for the Chrysler pick-up box [100,101]. This one-shot, 120-pound part is molded using a Dow Chemical SPECTRIM® resin. The part is fabricated with a "button-to-button" cycle-time goal of 10 minutes using a shuttle press and a sophisticated Cannon USA injection system. Very little has been published about a reported General Motors' S-RIM pick-up box [99,102].

A three-component S-RIM telescoping pick-up truck cargo area cover called the Top-Slider® is manufactured by Marmor Specialties. This product is a lockable, protective cover that provides maximum vehicle rear view visibility as well as the capability to haul bulky loads by retracting the two rear sections of the assembly. An ICI RIMLINE® resin system is used in this application.

The first commercial, non-automotive S-RIM application was a Xerox 2510 copier heat shield molded by AmBeck Plastics. This heat shield, which replaced a thermoformed part, consists of three pieces bonded together. AmBeck uses Ashland's Airmax® 1350 resin reinforced with 30% by weight continuous strand mat. This part must withstand a continuous operating temperature of 250°–300 °F with intermittent exposure to 600 ° for 6 minutes [22,92]. Xerox cut more than 40% off the cost of the thermoformed heat shield by switching to S-RIM [33].

In 1989 two molders introduced S-RIM shells for office chairs. Plastic & RIM Technology Systems, Inc. molded two seat backs and a seat base for the Decade office chair. These parts are 0.25 inch thick and are composed of continuous strand mat sandwiching two stitched layers of unidirectional fibers. A Mobay STR-500 resin is used in this part [33,103].

Ardyne Inc. is molding the seat backs, a base, and seat shells for a new line of Herman Miller office chairs (fig. 16). A complex reinforcement package is used to achieve integral spring elements in the one-piece Herman Miller side chair model [92]. Dow's SPECTRIM® MM 310 resin is used to fabricate these chair components [33].

The largest commercial S-RIM part, a two-piece 90-pound satellite antenna, was announced in late 1989 by Lucas Epsco, Inc., Northern Satellite Group (fig. 17). The two S-RIM parts are assembled to form a parabolic dish measuring 8 feet high × 8 feet wide × 1 foot deep. The S-RIM parts are reinforced with 40% by weight continuous strand mat and are surfaced with copper and acrylic paint. The resin matrix is a Mobay Baydur® STR-425 polyurethane. These parts are molded by Plastek Corp. a division of General Industries. The installed satellite antenna can survive winds up to 125 mph, temperatures from –76 °F to 140 °F, up to 4 inches of rain per hour, 20 inches of snow per hour, and 1 inch of ice on all surfaces. When disassembled both halves fit into a full-sized van. They can also go inside a standard elevator for assembly on a roof top [33,92,104].

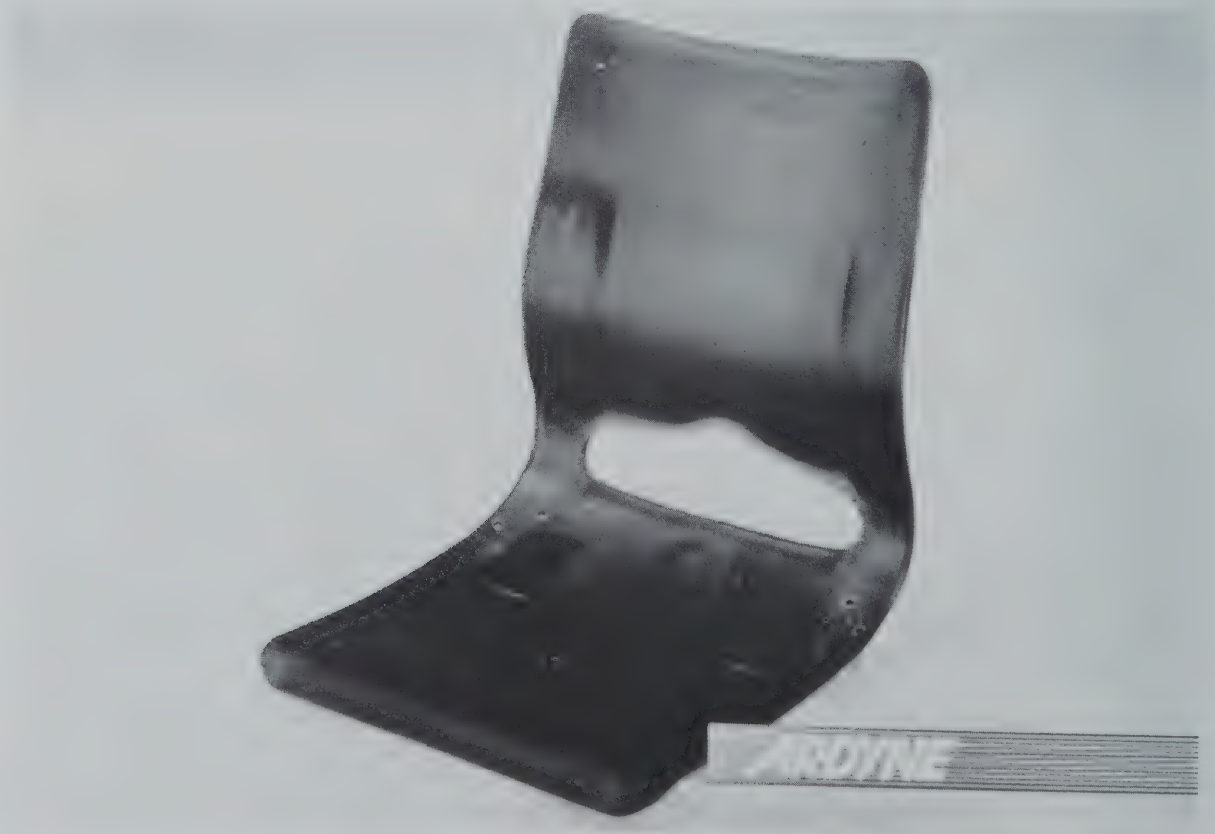

Figure 16. A photograph of a S-RIM Herman Miller seat shell (courtesy of Ardyne Inc.).

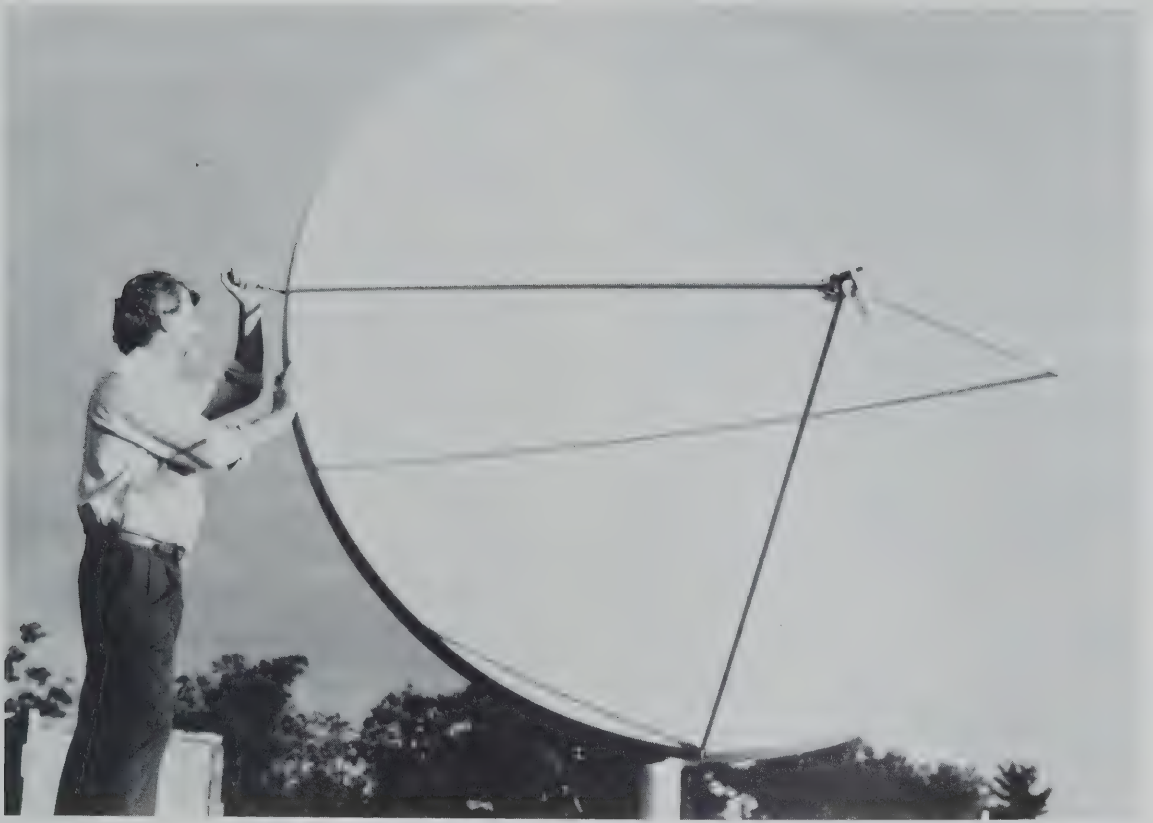

Figure 17. A photograph of a S-RIM satellite antenna (courtesy of Plastek Corp. and the Mobay Corp.)

6. Summary

S-RIM is a very attractive composite manufacturing process for producing large, complex structural parts economically. The main drawback of this process is that it is relatively new, so that some aspects of this technology are poorly understood and some crucial equipment remains to be fully developed.

If S-RIM is to achieve its potential, the development of economical preforming materials and manufacturing processes is essential. While the S-RIM resin suppliers have developed a wide array of potential composite matrices, little is known about: (1) their compatibility with existing fiberglass reinforcements, (2) the long-term stability of S-RIM composites in potentially degrading service environments [temperature extremes, chemicals, high humidities, fatigue loading, etc.], or (3) ways of improving their surface appearance.

Very little scientific work has been done to understand the reaction kinetics and molding time-temperature window for S-RIM resins. Coupled with a three-dimensional fluid flow model, this information would allow a molder to eliminate wasteful trial-and-error development of S-RIM processing conditions.

While the first commercial S-RIM part was molded only 5 years ago (1985), the technology has since made significant progress. Further development does not require revolutionary discoveries; rather the integration and application of existing technologies from other industries will lead to a fully unified and economical S-RIM manufacturing process.

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Structural Resin Transfer Molding

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Structural polymer-based composite materials are a key segment of the rapidly expanding field of advanced light weight materials. Unlike some of the competing materials, such as aluminum, high-strength steel, and magnesium, polymer composites lack extensive design tools, data bases, and a manufacturing infrastructure. While this deficiency may slow the implementation of structural composite materials, it also presents many opportunities for small- and medium-sized industries to formulate unique solutions to the various needs of the "infant" structural composites industry.

The process of resin transfer molding is one of the structural composite fabrication process currently viewed as having high potential for effective use in the automotive and commercial product industries. The process is also receiving increased interest from the aircraft and defense industries in applications where medium to high volumes of components are required. In this monograph I have attempted to identify key areas where developments are required or a supply capability is likely to be required.

The monograph first reviews the current components of the resin transfer molding process including the resin systems, reinforcements and equipment and identifies the unique capability of this process to form large, highly integrated, complex, high-performance structures. Likely markets and applications for resin transfer molded structures are discussed, including the evolutionary path from outer skin panels through derivative vehicle applications to the final goal of an all-composite vehicle structure. Finally, the limits of the current technology and the future needs of the resin transfer technology are detailed. Development of design tools which provide simultaneous optimization of part geometry, performance and processing has been identified as a major need. In addition, effective recycling technologies will also be required, as will cost-effective preforming methods for complex reinforcement arrays. The opportunities in supplying low-cost materials systems and tooling will continue at their current high level.

Key words: cost effective materials; HSRTM (High Speed Resin Transfer Molding); preforming; resin transfer molding; simultaneous design tools; structural composite materials in vehicles.

1. State of the Art of Current RTM Technology

Resin Transfer Molding (RTM) and Structural Reaction Injection Molding (S-RIM) are two similar processes which are well suited for the manufacture of large, complex, high-performance polymer composite structures. As in the case of any potential manufacturing technique, a thorough understanding of the advantages and limitations of the process is required before it can be effectively considered for design and manufacture of a component. RTM, in its most common form, is a closed mold, low-pressure process, in which dry-preshaped reinforcement material is placed in a closed mold and a polymer solution or resin is injected at low pressure, filling the mold and thoroughly impregnating the reinforcement to form a polymeric composite part. The reinforcement and resin may take many forms, and the low pressure combined with the preoriented reinforcement package provides a large range of component geometries, sizes, and performance options.

Figure 1 presents a schematic of the process. A preform of reinforcement fibers, in this case a stampable glass mat, enters the process as a roll of flat sheet material and is stamped into shape by means of a shaping die. The preform is preassembled with foam cores in three-dimensional box-sections, if desired, and the finished preform is placed in a mold and the mold is closed. A two-component resin system is then mixed in a static mixer and metered into the mold through a runner system. Air inside the closed mold cavity is displaced by the advancing resin front and escapes through vents which are located at the high points or last areas of the mold to fill. When the mold has filled, the vents are closed, the resin inlet is closed and the resin within the mold cures. Upon complete cure of the resin, the finished component is removed from the mold.

The S-RIM, or structural reaction injection molding, process shown schematically in figure 2 is quite similar to the RTM process. A preformed reinforcement is placed in a closed mold and a reactive resin mixture is impingement mixed under high pressure in a specially designed mix head. Upon mixing, the reacting liquids flow at low pressure through a runner system and fill the mold cavity, impregnating the reinforcement material in the process. The process derives its name from the RIM process, from which the resin chemistry and injection techniques have been adapted. The term structural has been added to indicate the more highly reinforced nature of the typical composite components manufactured by this process. Once the mold cavity has filled, the resin quickly completes its reaction. A completed component can often be removed from the mold in as little as one minute.

1.1 Some Attributes of the RTM Process

Both RTM and S-RIM are closed mold processes; i.e., the tool which forms the part is fully closed when the final shape of the part is determined. A closed mold process has two distinct advantages in that there are two finished surfaces for

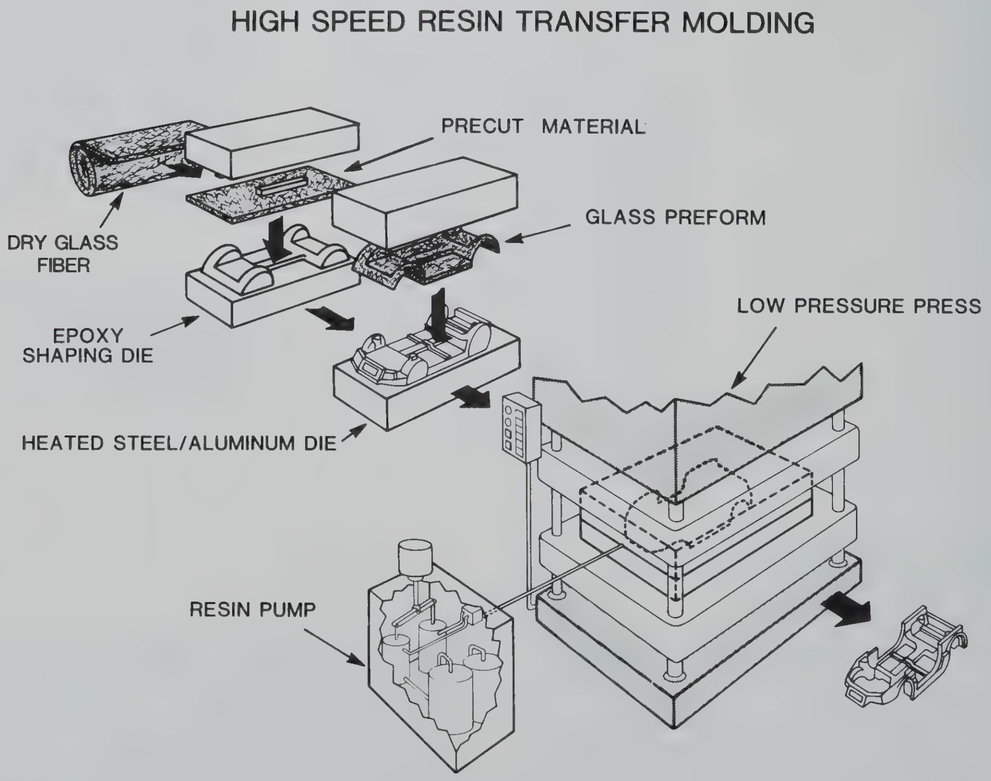

Figure 1. Schematic of an idealized HSRTM process.

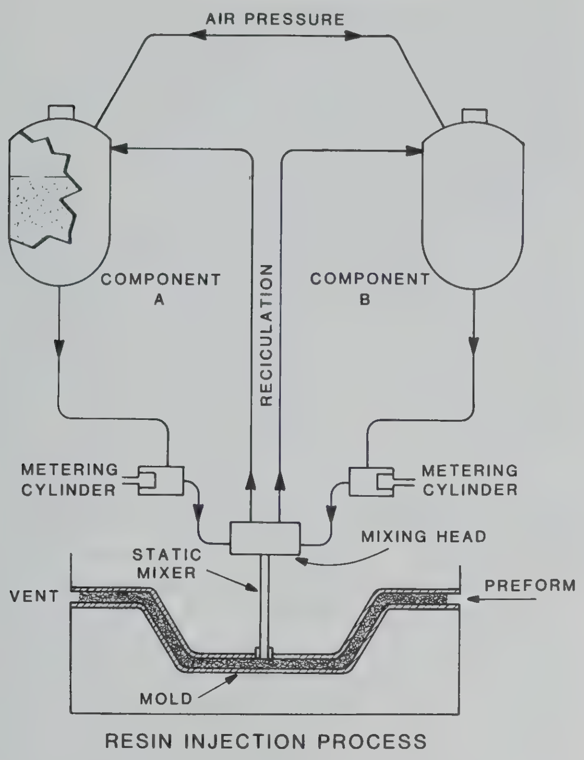

Figure 2. Schematic of the S-RIM process.

the component and lower styrene emissions if the resin system contains styrene. In the RTM and S-RIM processes there are two additional benefits due to the fact that the mold, unlike a compression mold or thermoplastic stamping mold, is completely closed to defined stops prior to the final part formation: more reproducible part thickness and minimum trimming and deflashing of the final part.

The use of a preplaced reinforcement preform provides the ability to place a variety of reinforcements in the precise location desired and to have it remain in position as the component is being molded. Both processes allow the use of a wide variety of reinforcement materials with glass, Kevlar®, carbon, and steel being the most commonly used today. Materials may be random, continuous filament random, or oriented continuous depending on the tradeoffs between complexity of the geometry, performance, weight, and cost of the preform. If large amounts of random reinforcement material are used, consideration must be given to minimizing "washing" or movement of the fibers due to resin flow near resin inlet gates.

Low injection pressure is another attribute of both the RTM and S-RIM processes. Depending upon the volume fraction of the reinforcement preform and the orientation and type of reinforcement, the injection pressure versus time relationship for a part will vary. Some simple components with low (10–20 volume %) volume fractions of reinforcement will fill rapidly at pressures in the 10 to 20 psi range. More complex components having higher volume fractions of reinforcement (30–50 volume %) may require pressures in the 100 to 200 psi range. If low pressure is a requirement for a given component, such as a large roof panel or similar large area part, the injection pressure can generally be maintained at a low value and the fill time extended. In cases where low pressure and fast fill times are both required, the preform construction must be carefully tailored to promote a rapid low-pressure fill. Another attribute of RTM which also enables increased part integration is the capability of the process to produce closed box sections in a single piece through the use of integral cores in the reinforcement preform.

RTM, like compression molding and thermoplastic stamping, allows the use of molded inserts. Inserts in RTM are normally included as part of the preform, which simplifies loading of the mold and eliminates loose metal pieces that, if misloaded, can damage the mold.

The RTM process allows a wide range of size, shape, and design detail flexibility. In general though, the process is best suited to the manufacture of large, non-symmetric, three-dimensional shapes having some closed box sections integrated into the design.

1.2 Applications Using RTM Techniques

The majority of RTM applications today fall into the prototype, low-volume, specialty product category. The low cost of simple RTM tooling and the high level of physical properties attainable make this process well suited for the production of low volumes of complex, high-performance parts having large areas. New developments in preform fabrication, tooling, and resin systems are beginning to extend the utility of the process into the area of higher production volumes.

1.3 Resin and Reinforcement Materials for RTM

One of the major advantages of the RTM process lies in the wide variety of resin and reinforcement systems that can be employed in the process. The resin type can be varied to achieve the desired cost and performance targets for a design, as can the type, level, and orientation of the reinforcement system. This flexibility results in a seemingly endless series of material options, but it is this flexibility that also makes material property characterization and the availability of design data a major deficiency in today's polymer composite industry.

1.3.1 Resins There are numerous resin chemistry choices for an RTM component. Any resin must have the ability to fill the mold completely, wet-out the reinforcement, and cure or freeze to a solid state with the desired physical properties. RTM offers such a broad variety of capabilities it is difficult to further define resin attributes.

In high-performance applications viscous epoxy resins can be molded using slow cycles. Where cycle time is critical, low-viscosity vinylester, acrylamate, or RIM resins based on urethane chemistry can be injected very rapidly into the mold. Although it is currently not feasible to mold thermoplastic materials using RTM procedures, experiments in the area of non-reinforced thermoplastic RIM provide promise that in the future the attributes of thermoplastic systems can be applied to RTM molded structures.

Currently RTM systems tend to use thermoset chemistry. Viscosity of the resin is low and rapidly penetrates reinforced preforms with up to 50 weight % glass. General purpose thermoset resin systems provide high levels of strength and stiffness but do not yield a Class-A surface. RTM resins are typically low-viscosity liquids in the range of 100 to 1,000 cPs. Normally resin systems will be two component in nature and will require a mixing ratio in the range of 100 to 1 prior to injection. The liquid reactants part A and part B can be mixed at low pressure using a static mixer.

S-RIM resins are similarly two-part, low-viscosity liquids (in the range of 10 to 100 cPs at room temperature). They are highly reactive in comparison to RTM resins and require very fast, high-pressure impingement mixing to achieve thorough mixing prior to entering the mold. Mix ratios of typical systems are near 1:1, which is desirable for rapid impingement mixing.

There are some polyester and epoxy RTM systems which provide a near Class-A surface. Limitations exist, however, in their ability to be painted at elevated temperatures and in the type and level of reinforcement which can be used. Future work will likely make the molding of some semi-structural body areas, such as roof panels, feasible.

1.3.2 Reinforcements Reinforcement material selection is likewise nearly limitless in RTM. Glass (both E and S-2), aramid, and carbon fibers are commonly used. Wood fiber and other synthetic fibers such as polyester and polyethylene are possibilities depending upon requirements. Metal can be an excellent choice for local reinforcement in a structure. Metals should be noncorrosive or properly protected against moisture or other environments prior to inclusion in the preform.

Reinforcement content can be varied throughout the same component as can reinforcement type and orientation. The lower limit of reinforcement content is generally defined by strength and stiffness requirements. It is desirable to maintain reinforcement content at or above a minimum level which will fill the entire cross-section of the part to avoid resin-rich surfaces or corners, which tend to crack due to excessive resin shrinkage if unreinforced. Corner geometry must normally be considered if the resin system used tends to crack when it is not fully reinforced. In most preforms the reinforcement will tend to pull tight around corners as the mold closes leaving a resin rich area. If this condition is unacceptable, the shape of the mold can be altered to conform to the deformed shape of the preform. When molds having seals rather than pinch offs or shear edges are used, it will be difficult to keep reinforcement at an edge. Where possible, shapes should be designed that do not require reinforcement at the outer edges. Caution should be exercised any time an edge is required to carry high stresses. An example of this would be keeping reinforcement at the edge of a door opening in a vehicle body or closure panel.

Maximum reinforcement contents are governed by resin flow requirements and glass packing factors. Reinforcement content up to 70 volume % is possible, but resin injection time will be long. Levels of random reinforcement will be lower than those for oriented reinforcement due to the lower packing efficiency of the fibers. If levels in excess of 40 volume % random materials are used, damage to the fibers is likely to occur when the mold is closed, with a subsequent reduction in physical properties. In general, compression molding will provide higher reinforcement content allowables due to the higher forming pressures used.

1.3.3 Preforms Preforming is currently a major technological barrier to the further use of RTM molded composites in a wide variety of high-volume automotive applications. Several candidate preforming processes have been in development over the past few years, and their current capabilities vary from production ready to processes requiring much additional work that may be ready for use in the distant future.

Random mats and engineered fabrics in the form of flat roll goods are normally the most cost-effective alternative for an RTM part. These reinforcements can be laid into large simple shapes, cut, folded, or otherwise manipulated as required. When foam cores are required, wrapping with material prior to placement in the mold is sometimes adequate. More complicated shapes require some preshaping of the material prior to placement over a core or into a mold. Several types of stampable or thermoformable random glass-mat materials can be used for components with considerable geometric complexity. The thermoformed preform shown in figure 3 was stamped from 6 oz./ft.^{2} glass mat prior to placement over a urethane foam core.

Cut-and-place fabric preforming is currently available for low-volume applications where high-performance levels are required. Examples of high-performance automotive components preformed by such a process are shown in figure 4. Both the Escort front structure [1] and Aerostar crossmember [2] utilize a series of individual pieces of glass fabric and random glass mat, cut to complex shapes, and attached by sewing or stapled to a urethane foam core. Although preforms made by this technique fulfill all the mechanical performance requirements, the process of cut-and-sew is too expensive and slow (even if automated) to compete effectively with steel in most applications.

Spray-up preforms are also commercially available and at high volumes. This process utilizes a reinforcement chopper gun to apply a layer of random chopped reinforcement (normally glass) to a porous screen. A vacuum applied to the screen holds the fibers in place, and a binder applied coincident with the fibers is subsequently cured to hold the preform in shape. This type of preform has near-net-shape capability and low waste, but in its current state of development the overall physical properties are too low to enable it to serve as a weight-effective primary structure in an automobile. With the addition of continuous reinforcement and improved sizing and binder chemistry, the spray-up process holds great potential to be a future cost effective preforming process.

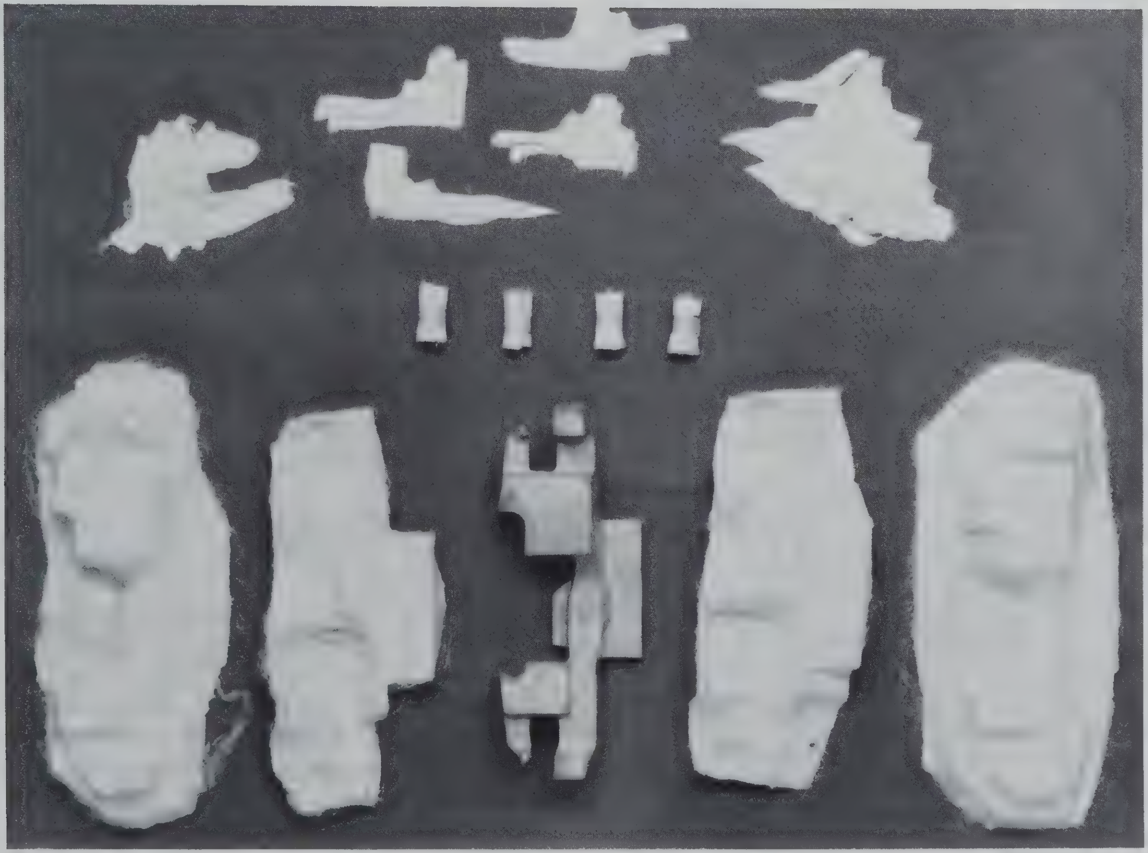

Figure 3. Stamped preform for an all-wheel drive van.

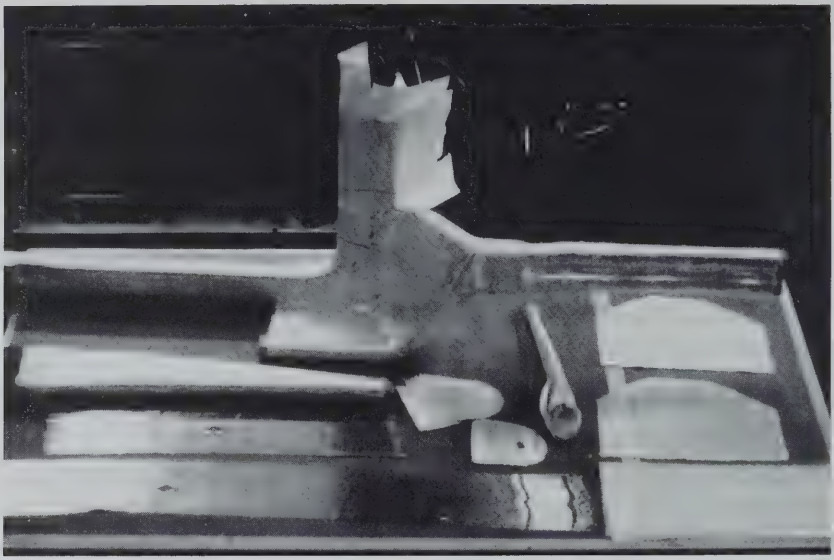

Figure 4. Cut and sew preform for a vehicle front structure.

Knitting and braiding are also low-waste near-net-shape preforming processes. Currently their speed of reinforcement placement tends to be slow and costs high. Braiding is limited to simple shapes but appears to be ideal for localized high-performance attachment points and reinforcements as additions to a larger preform. Knitting will require further development of unique stitches to eliminate the current weak resin-rich planes and overly tight radii in the reinforcement yarns which tend to reduce physical properties of knitted preforms.

The stamping of random mats and continuous-weft knit materials for local reinforcement of high stress areas is an available technology for automotive components which appears to be the best choice for near term work based on cost and performance. The stamping process is rapid and several materials are currently commercially available. Although these materials are typically at the low end of acceptable physical property levels, they can be locally reinforced with oriented continuous material and stamped as a sandwich. Stamping requires further development in the area of waste reduction, and more conformable continuous-oriented reinforcements must be developed if the process is to reach its optimum level of development.

Finally, it is wise to remember that as the preform size increases, it becomes increasingly difficult to manipulate the reinforcement into the mold. In some cases it may be more advantageous to fabricate smaller sections of the structure and assemble them.

1.4 Equipment

The most elementary form of resin transfer molding equipment is depicted in figure 5. A simple, two-dimensional preform of glass mat is formed into a concave mold cavity, and the upper half of the mold is closed on the reinforcement. The outer perimeter of the mold is left open to allow the displaced air to escape as the resin enters and fills the mold from the center to the edges. As the resin reaches the edges of the part, it simply drains out into a catch basin. When injection is complete, the component is allowed to cure and is removed from the mold and trimmed. While more sophisticated RTM systems are normally used, the physical properties achieved using this simple system approach the properties of the most sophisticated RTM systems.

A sophisticated RTM system sometimes referred to as High Speed Resin Transfer Molding (HSRTM) is shown in figure 6. This process utilizes a complicated preform made using one or more of several high-speed preforming processes and typically incorporating foam cores, molded-in inserts, and high-performance attachment points. Tooling is designed for high volume and rapid cycle times and is normally steel or nickel shell construction for maximum durability. Resin is introduced using automated resin handling equipment, and the resin inlet and air outlet (vent) are accomplished with automated self-cleaning nozzles. The HSRTM method uses the same resin sys-

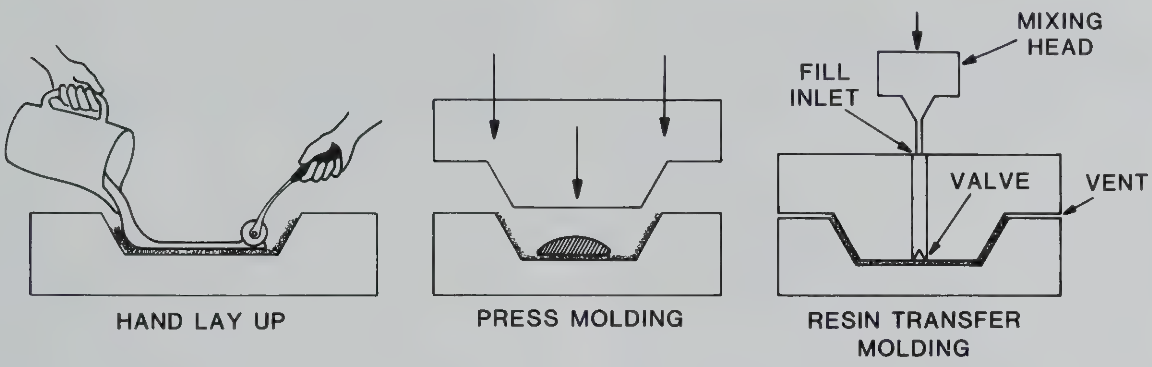

Figure 5. The basic RTM process.

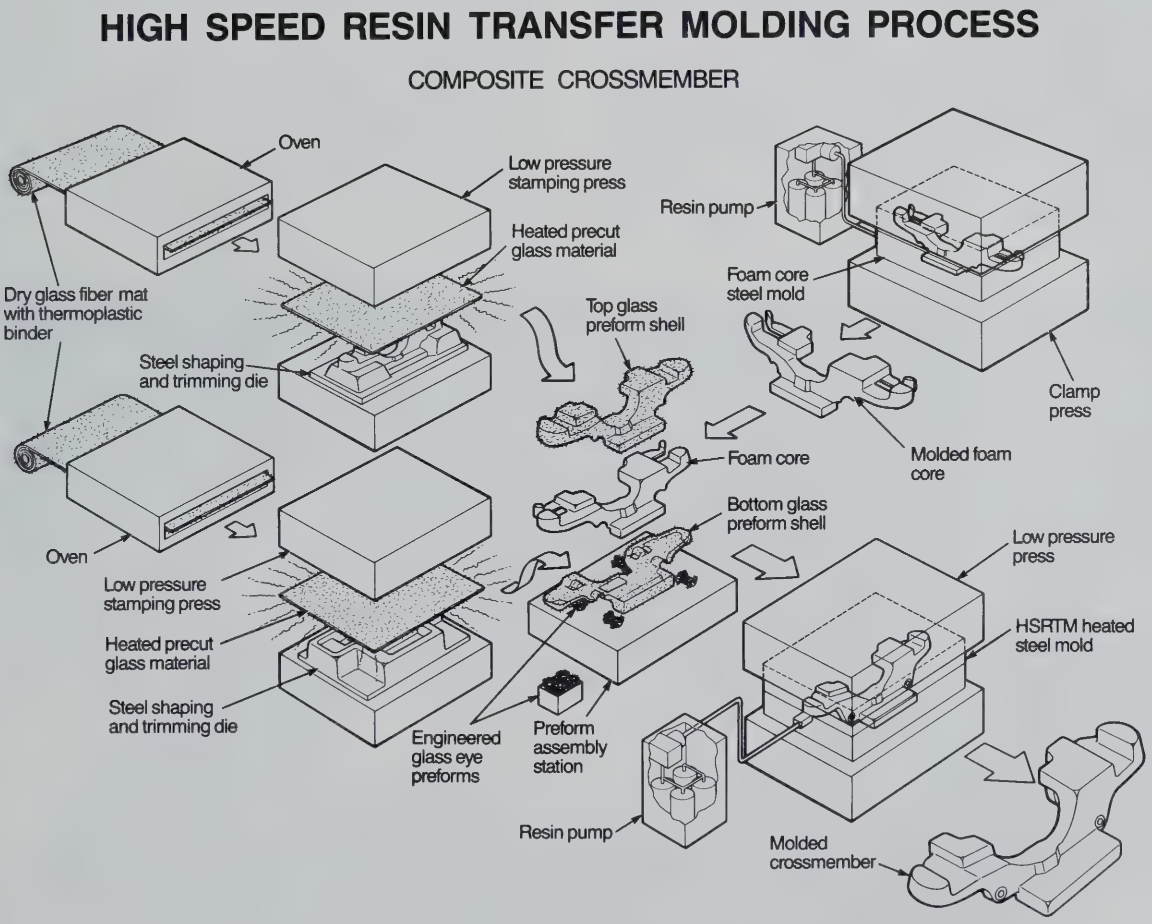
HIGH SPEED RESIN TRANSFER MOLDING PROCESS
COMPOSITE CROSSMEMBER
Oven
Low pressure stamping press
Heated precut glass material
Dry glass fiber mat with thermoplastic binder
Steel shaping and trimming die
Resin pump
Foam core steel mold
Top glass preform shell
Clamp press
Molded foam core
Foam core
Bottom glass preform shell
Oven
Low pressure stamping press
Heated precut glass material
Steel shaping and trimming die
Engineered glass eye preforms
Preform assembly station
Low pressure press
HSRTM heated steel mold
Resin pump
Molded crossmember

Figure 6. An actual HSRTM process for an automotive crossmember.

tems employed in the slower RTM process, but the chemical reactivity of the systems can be increased to yield cycle times of 1 to 6 minutes with heated tooling. The use of highly automated equipment for HSRTM makes the process very similar to (S-RIM).

1.5 Supporting Technology

Before any technology can be reliably used in a high-volume application, adequate design and process modeling tools must be available. In most computer-assisted component designs done thus far for RTM manufacturing, a classical NASTRAN or similar finite element analysis is used [2]. As a subprogram to the finite element analysis, some type of laminate analysis is also used to develop the element properties for the NASTRAN analysis. Because of the flexibility available in designing fiber orientations in a preform, the design in RTM can be very efficient with respect to material use. In the limiting case, only those reinforcements carrying load need to be included. Available laminate analysis can place reinforcements only in the X and Y planes, but as more sophisticated preform technology is developed, such as three-dimensional knitting and weaving [3], more sophisticated analytical techniques [4] are also being developed.

Finite element and finite difference techniques are also under development [5–7] for the prediction of resin flow through the RTM preform during manufacture. Ultimately, prediction of flow may be as critical as prediction of physical properties when a unified RTM design code is finally available. There is currently significant work in progress both with respect to optimized preform designs and computer-assisted process selection.

1.6 Experience and Data Bases

Experience in structural composite programs [8] has indicated that for structures to be adequate in performance and yield weight savings (over a steel design) on the order of 30%, material properties must exceed quantifiable minimum values for tensile strength and tensile modulus. The majority of structural composite applications currently under study for vehicles are stiffness dominated; thus tensile modulus over the anticipated strain design level is critical. Monotonic tensile strength, while normally adequate given sufficient stiffness, is also important. The range of values determined based on the referenced demonstration programs are:

tensile modulus: 2.2–4.5 million psi (15.15–31.01 GPa)
tensile strength: 30,000–40,000 psi (206.7–275.6 MPa)

These properties are the design level properties after allowances have been made for fatigue and environmental and temperature effects.

The range of operating temperatures experienced in an automobile is dependent on the location of the structure relative to heat sources. Sources of heat are normally the drive train, exhaust system, and direct or reflected sun load. Temperatures can range from ambient to greater than 170 °C. Any composite system must retain its physical properties above the minimum levels at the anticipated maximum operating temperature. Impact resistance is a critical low-temperature consideration for structural composite design, but it is currently difficult to characterize and input into the design process.

1.7 Prototyping

Resin transfer molding is an excellent process choice for making prototype components. Unlike processes such as compression molding and injection molding, which require tools and equipment approaching production level to accurately simulate the physical properties achievable in the production level component, RTM allows representative prototypes to be molded at low cost. It should be noted that in some cases, RTM can also be used to prototype components designed for other processes, in particular SMC. When simulating other processes, the RTM component will typically have properties that exceed the production level product.

When prototyping with RTM, less reactive resins are generally used allowing long fill times and easier control of the vents. Tooling is normally low-cost epoxy but could be made from any impervious material which would contain the resin. Prototype preforms are made by cut-and-sew methods, and any foam cores used are machined to shape. Sizes can range from small components to very large, complex, three-dimensional structures. RTM provides two finished surfaces and controlled thickness, and it requires no auxiliary vacuum or autoclave equipment. Other processes used for prototyping such as hand layup and wet molding give only a single finished surface and dimensions in the thickness direction are uncontrolled.

2. Applications and Markets for Composite Structures

The majority of RTM structures today fall into two categories: (1) low-volume structures where the RTM process is used to manufacture large, relatively complex parts, and (2) small, simple geometries which are manufactured in low to medium volumes. The challenge for the composites industry will be in extending the potentially useful RTM technology into the higher volume markets, areas now dominated by metals. In the transportation sector this extension will likely be driven by the need for lower weight structures required to achieve increased fuel efficiency and by a need for increased styling flexibility at acceptable investment levels.

2.1 Production Volume Capabilities of RTM Technology

Today's resin systems for RTM and S-RIM are capable of very rapid cycle times due, in part, to the low initial viscosity. The initial viscosity of a typical resin system is in the 100 to 1,000 cPs range as it reaches the mold inlet. Cycle times for high-volume applications will vary depending on the complexity of the component and degree of part integration achieved. For a simple component such as the tire cover shown in figure 7, a 1-minute cycle has been commercially achieved at a production rate of 1.2 million components per year. For a component such as the complex crossmember shown in figure 8, a cycle time of 6 minutes would be realistic with current technologies. The economic feasibility of complex components at production levels of 10,000 units or more is yet to be demonstrated. Both the RTM and S-RIM systems have the capability of achieving rapid cycle times, and once either process has been found appropriate for fabrication of a given component, the ultimate choice of a resin system will likely be made on a cost/performance basis.

2.2 Today's Differentiation of RTM and S-RIM

The S-RIM process presently tends to utilize preforms that are less complex in construction and lower in reinforcement content than the RTM process. The S-RIM resin systems currently available build viscosity rapidly, which equates to a higher average viscosity during mold filling. The lower reinforcement content and typically larger percentages of random to continuous oriented reinforcement help to offset the effects of the higher viscosity. Flow distance for a typical S-RIM system is limited to 2 to 3 feet from the inlet gate; thus current S-RIM applications tend to be of simple geometry.

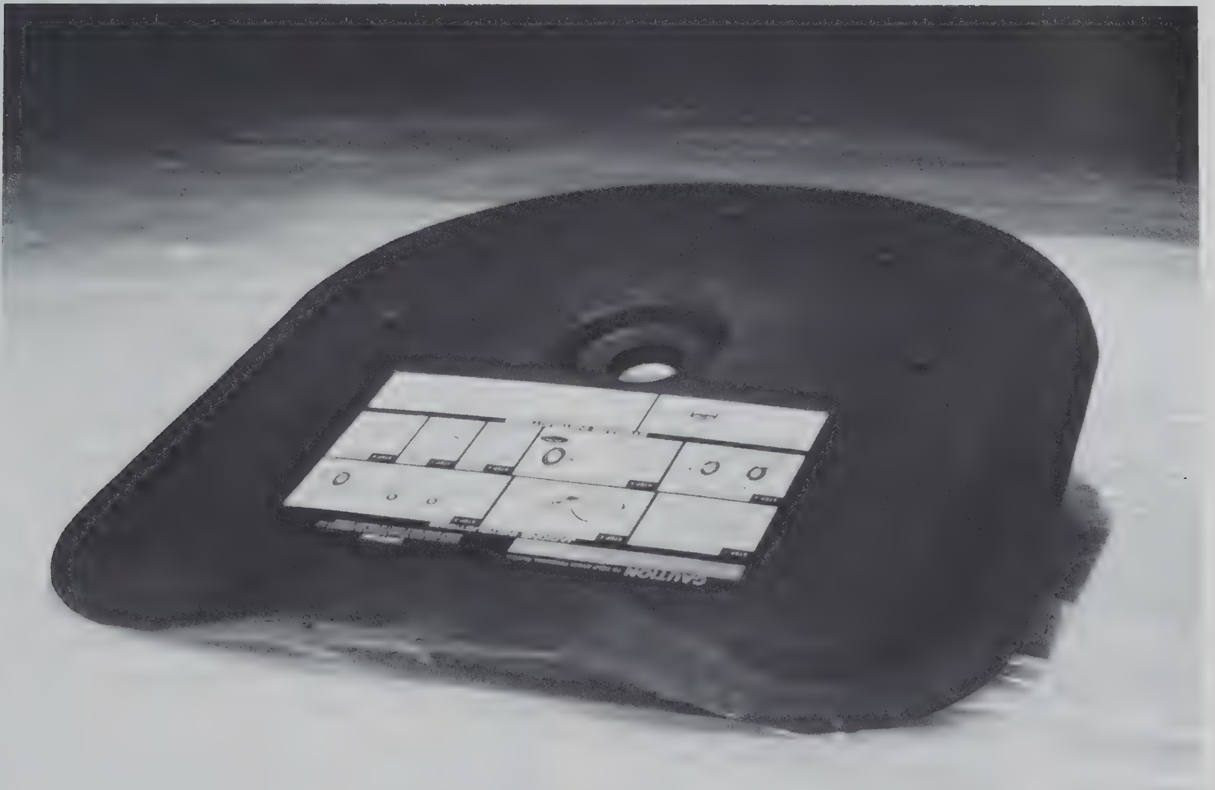

Figure 7. Spare tire cover manufactured by S-RIM.

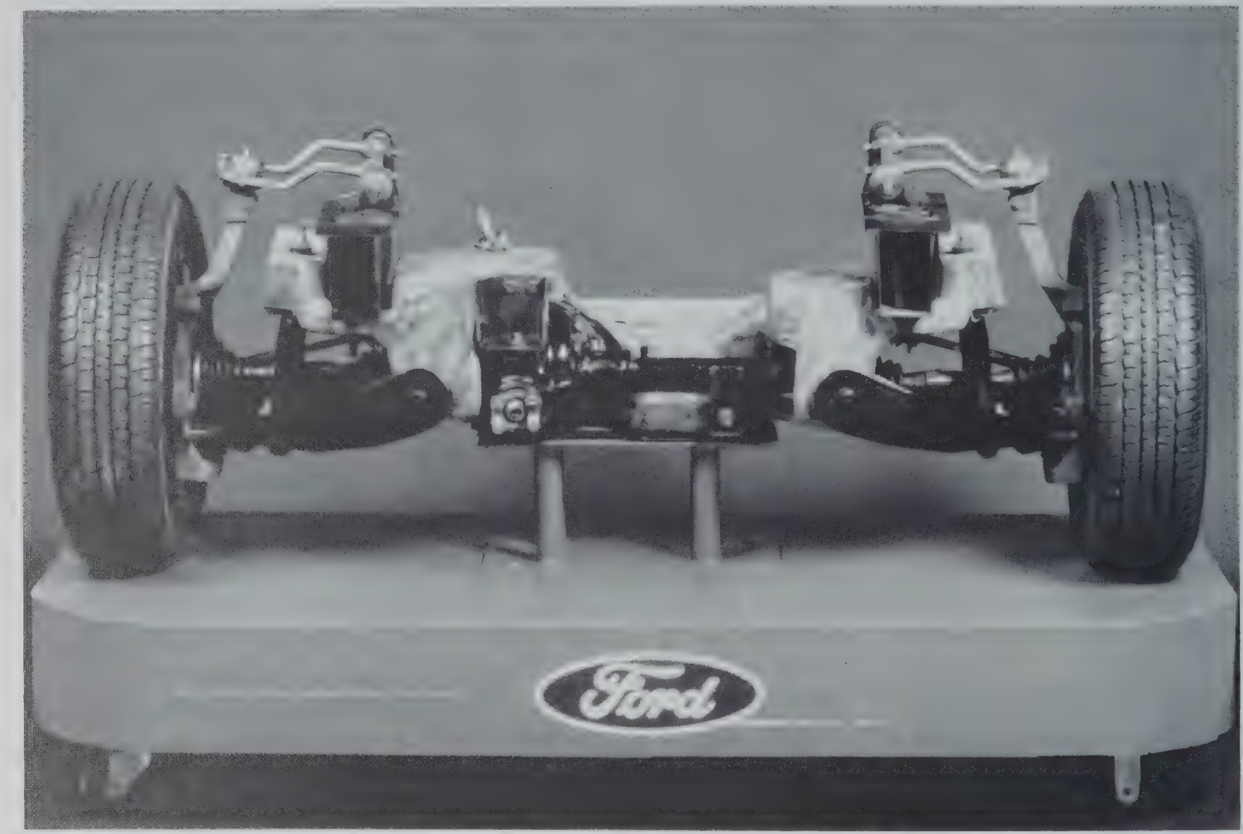

Figure 8. All-wheel drive van crossmember.

2.3 Application of RTM Processes for Vehicles

The success of non-structural plastics throughout the vehicle in the last decade has led to increasing interest in the application of plastic-based materials in semi-structural and fully-structural segments of the automobile. Such inroads have already begun, as evidenced by the increasing occurrence of skin panels and bumper systems. There remains, however, a vast opportunity for increased usage even in these semi-structural areas. There is essentially no application of plastic-based RTM molded composites in structural applications in high-volume vehicles, although these materials are evident in very low-volume specialty vehicles such as the Lotus.

The Lotus vehicle is manufactured by a process referred to as the Vacuum Assisted Resin Injection (VARI®) process. As currently practiced, the process uses epoxy tooling similar in nature to high-quality prototype tooling. Large dry reinforcement preforms, including shaped glass mat and foam cores, as well as local areas of continuous glass fabric, are loaded into two-piece molds, and the molds are closed and sealed. The molds require no press and only minimal clamping because after closing, a vacuum is applied to the tool and atmospheric pressure forces the tool to remain closed. Resin is metered into the tool and completely fills the component with a slight vacuum still remaining in the system.

Another derivative of the RTM process which encompasses a novel resin delivery technique to reduce cycle times or impregnate higher reinforcement volume levels is used to manufacture Matra vehicle components. While essentially a resin transfer molding process (or, as it is sometimes referred to in Europe, a resin inject process), the Matra version of the process reportedly meters the resin into the mold while the mold is still slightly open. This allows the resin to flow into the mold rapidly by not having to move through the preform to enter the mold. When the complete resin volume is in the mold, the inlet is closed, and the mold is closed and compressed to cause the resin to thoroughly impregnate the preform. A similar molding technique called *matched die molding* or *squeeze molding* utilizes a compression process to complete the wet-out of a preform and has been under development and refinement in the United States since the early 1950's by Morrison Molded Fiberglass. Further details of the process are available in articles by Morrison [9].

2.4 Scenarios for Future RTM Implementation in Transportation

The cost-effective production of derivative vehicles presents a new challenge to automotive material and design engineers. There is an increasing demand in the marketplace for a number of vehicles which are in some respect distinctive from other, similar offerings. Currently there are some 600 nameplates in the American automotive marketplace [10], with that number likely to grow over the next decade. To be viable for production, derivative vehicles must return adequate profit at low volumes. The use of composite structures appears to be one alternative material-driven strategy which can, through the use of large-scale part integration and high specific physical properties, provide truly unique design potential at the low investment levels required for economic feasibility at low volumes.

In considering the usage of radically different materials in automobile applications, the vehicle can be subdivided into two major segments requiring widely divergent properties. The outer skin panels are basically semi-structural in nature (with certain exceptions, e.g., rear quarter panels) in that the major requirements are high-quality surface finish and sufficient rigidity to yield the appropriate vibration and deflection characteristics. The second major structure is the body shell (the body in white) which provides the structural integrity of the vehicle and absorbs all the primary durability loads, meets crash requirements, and provides overall vehicle dynamic characteristics. From a materials and manufacturing viewpoint, the separation between these two overall vehicle concepts is in the different characteristics required from the individual components or structures. Thus, in considering the strategies for utilization of fiber-reinforced plastics, the properties and processes of these materials must be tailored in quite a different manner dependent upon the application. In addition, in either concept, not all areas of the vehicle need to be completely replaced by composites but can, of course, consist of a mixture of materials. This hybrid approach is already evident in skin panels and will unquestionably be extended to structural applications.

2.4.1 Outer Skin Panels The application of plastics and composites to outer skin panels is growing rapidly but in a somewhat fragmented manner. Some manufacturers are taking the approach of utilizing such panels on a selected basis, for example in hoods and/or deck lids, and some typical vehicle applications are shown in figure 9. In a few selected instances, the approach of utilizing composites for the complete outer skin has been used, with the Fiero and Corvette being the best-known North American examples and the Renault Espace being a well-known European example.

An exploded view of a current concept of composite outer skins is shown in figure 10. The clear preference emerging from all the developments in outer skin panel technology is the application of compression molded materials (SMC) for horizontal panels combined with a reaction injection molded (RIM) or thermoplastic injection molded material for vertical panel applications. The logic behind this materials mix is the difference in stiffness and thermal expansion of these two classes of materials. The horizontal panels require significant stiffness and reasonably low coefficient of thermal expansion, and SMC materials (25% chopped glass, 25% polyester, 50% filler) are the only polymer-based composites currently suitable for these applications. In addition to these physical requirements, there is the all-encompassing need for a Class-A surface finish. The vertical panels take advantage of the high toughness of thermoplastics to provide "friendly" features such as dent resistance. In addition, the quality of the thermoplastic-based materials is comparable to steel because the processing techniques for thermoplastics produce outstanding surface finish. In the vertical panels, the low stiffness and high thermal expansion of the RIM or injection molded thermoplastic materials are more easily compensated for in the design.

2.4.2 Derivative Vehicle Structures This concept consists of a molded composite upper body structure adhesively bonded to an existing steel platform. The drivers for using this type of structure include reduced investment for derivative vehicles, the availability of a highly differentiated vehicle for marketing advantages, and the potential for reduced design time due to carry over of the more engineering intensive chassis components. The upper structure can be fabricated by molded SMC or resin transfer molding, and the nature of this structure will depend on which process is utilized.

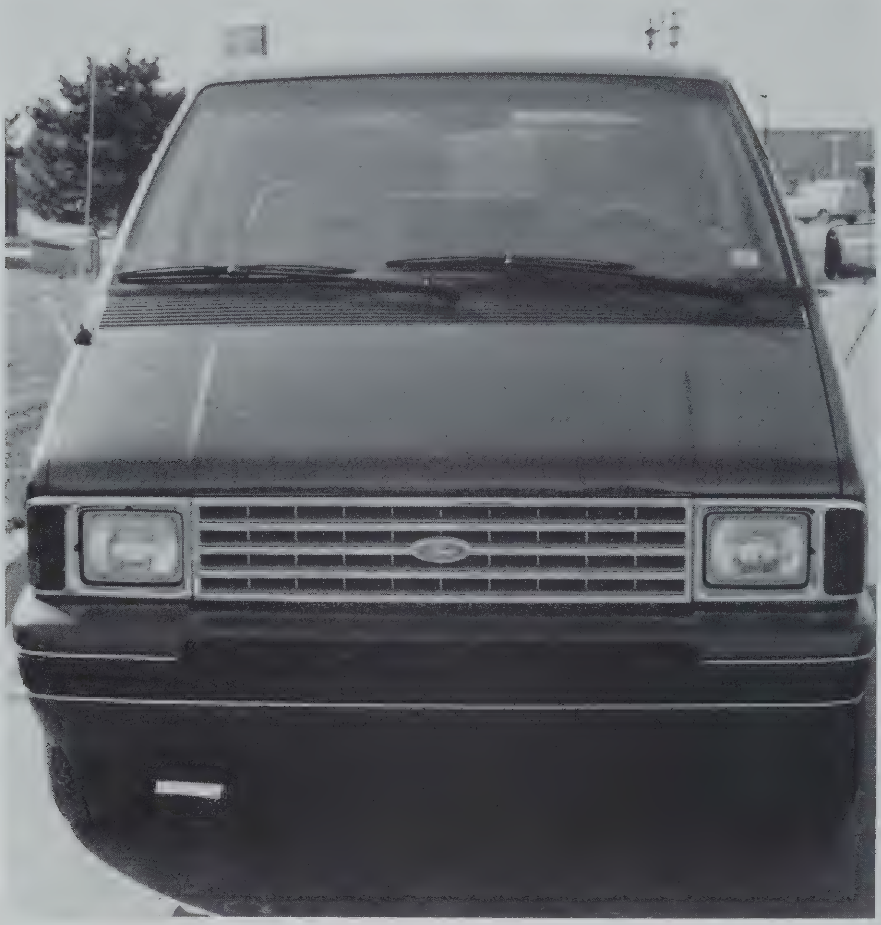

Figure 9. Composite outer panels for the Aerostar van.

This concept, shown in figure 11, is identical to the SMC approach, with the exception that it consolidates the two-piece assemblies of the SMC concept into single RTM structural elements. The resin transfer molded process can also consolidate the entire body structure into a single piece. Economics of manufacture may dictate that the structure be divided into additional pieces, but there will be significantly fewer pieces than in the SMC approach.

Additional benefits realized using this approach as opposed to the SMC approach include a reduction in tooling costs and further reduction in assembly costs. Reduced molding pressures allow the molding of larger components and lower the energy requirements of the process. In addition, because of the more optimum orientation of reinforcing fibers, increased structural integrity and higher overall stiffness at lower weight are anticipated.

2.4.3 Complete Composite Body in White To achieve the ultimate use of composite materials in a vehicle structure, it is likely that RTM could be used to produce a single, large, integrated body structure. The schematic in figure 12 shows this structure as a single piece, but once again economics of manufacturing may dictate that it be subdivided into several structural modules. In this concept, all structural functions are performed by the composite including management of crash energy. A Class-A surface is not required in this concept because additional surface panels can cover the exterior of the chassis. A Class-A surface capability would be desirable for some areas such as the rear quarter panels or roof.

The feasibility of this concept requires the RTM process because of its rigorous structural requirements. (Compression molding cannot be used for such large integrated structures.) Resin transfer molding provides closed boxed sections without

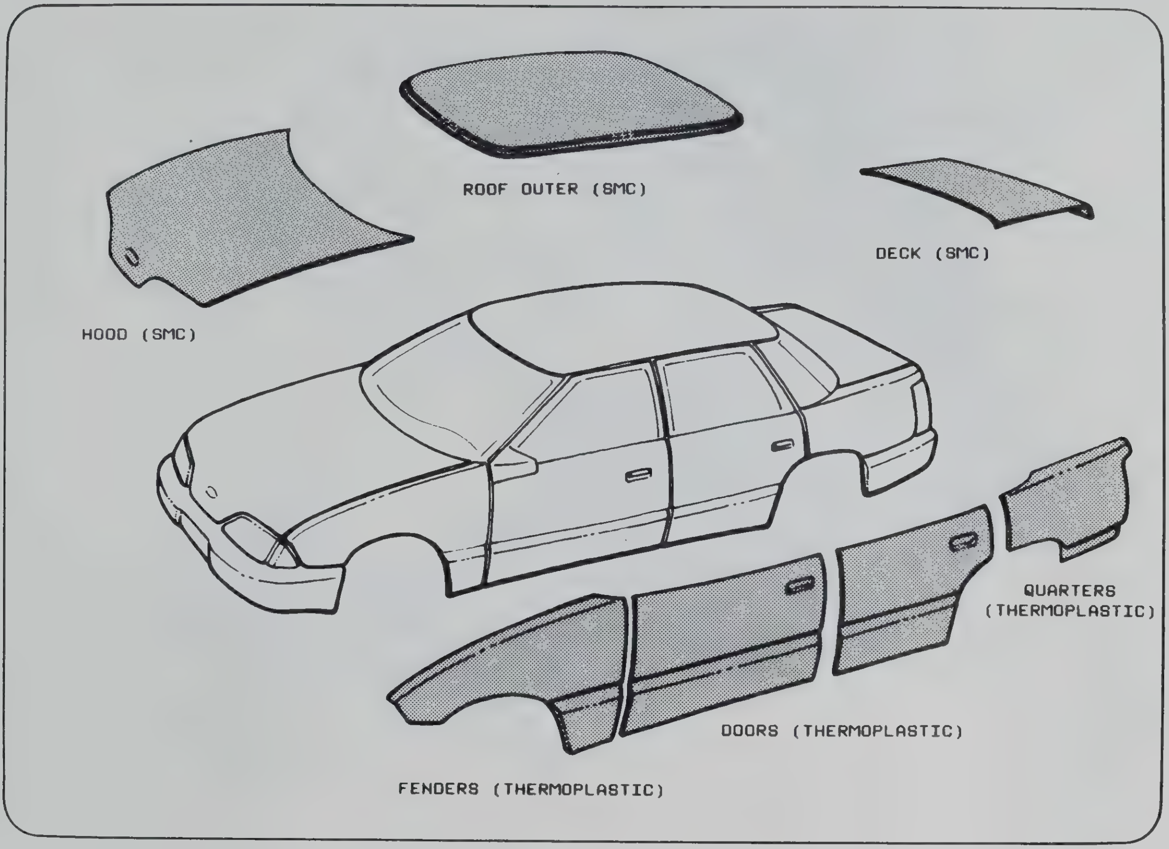

Figure 10. Full implementation of composite skins.

joints, giving optimum performance at a low weight. This approach, however, has more unknowns and presents more risks. Crash energy management using a totally composite structure must be extensively evaluated. Development of the manufacturing process for large integrated structures using the RTM process must also be continued. The area of cost-effective preforming of reinforcement materials requires special attention.

2.5 Barriers to Structural Composite Implementation

For composite materials to gain increased use in automotive applications they must, in the long run, be more cost effective than the competing alternative material systems. Short-term perturbations due to new government regulations and unusual consumer demands may temporarily provide an impetus, such as weight savings, for the use of more expensive materials, but over time the most cost-effective materials systems tend to capture the applications. Achieving weight savings of 30% can realistically be expected for a conventional structural composite design, but the necessity to do so in a cost-effective manner exposes several cost-related issues. A problem exists with composite materials in that the manufacturing issues are hard to quantify and thus tend to be costed in a very conservative manner. Also the volume sensitivity of material prices are largely undetermined for composites. Consumer attitudes, which are often given a positive value to offset higher costs, are known only for a limited number of specialty applications, and thus the true life-cycle costs of most material substitutions cannot be easily calculated. Given this uncertainty, a relationship between material cost and performance is proposed as a useful way to evaluate the potential of candidate composite systems.

2.6 Cost/Performance Driven Applications

Aerospace applications of structural composite materials have historically demanded the ultimate in performance and complexity. Materials such as

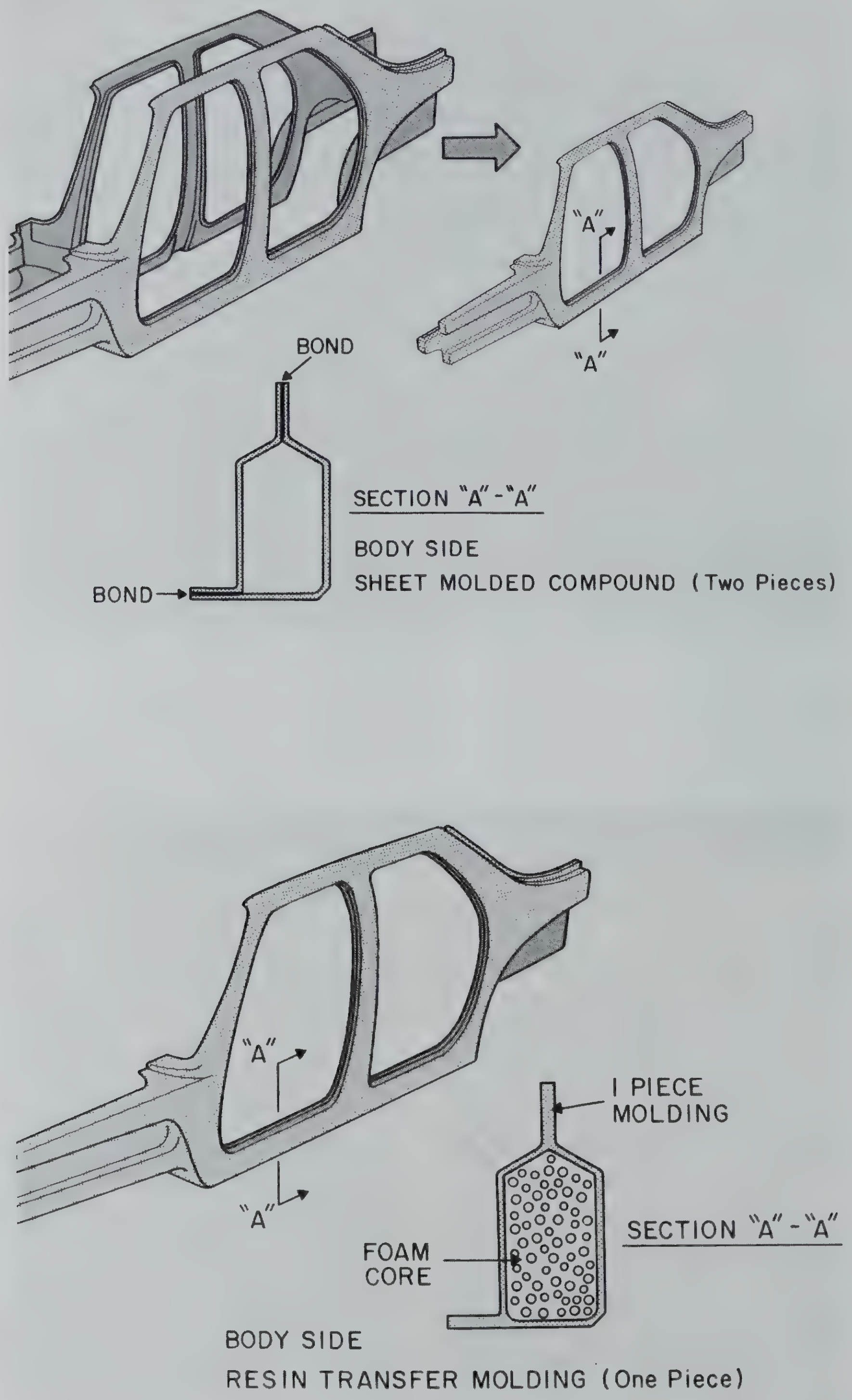

Figure 11. Niche vehicle using SMC (top) and RTM (bottom) structures.

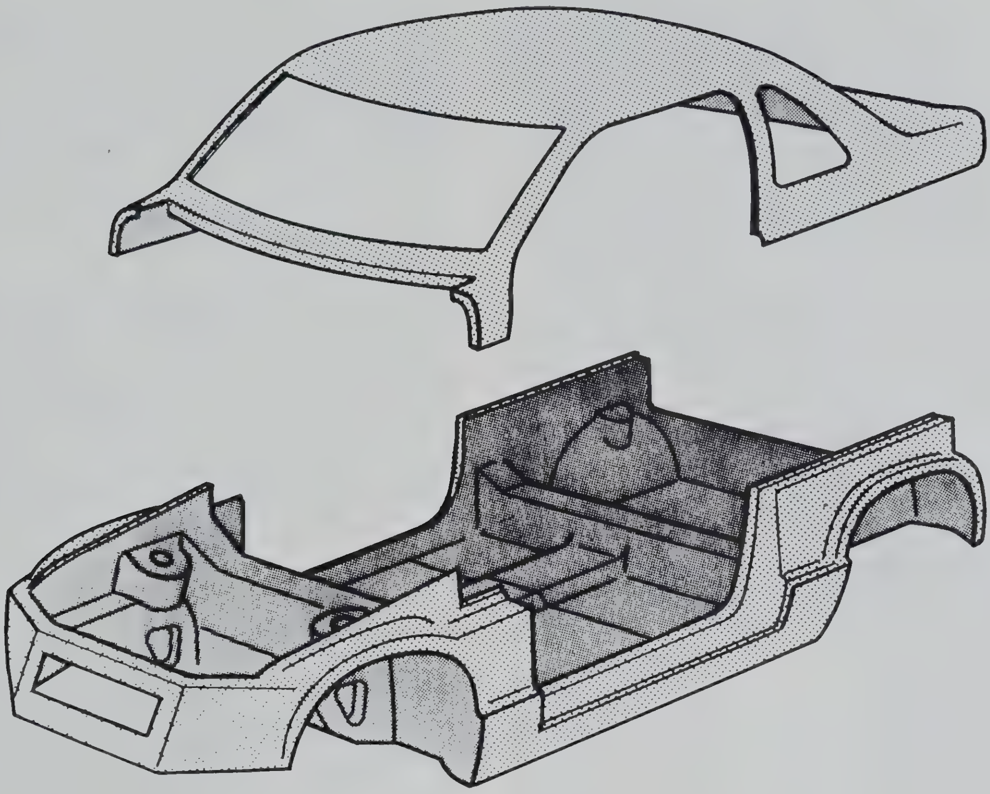

Figure 12. Full-body structure using RTM technology.

epoxy resin and graphite reinforcements are precombined in a prepregging process to achieve the ultimate in fiber wet-out and interface compatibility. A carefully controlled process of hand layup is then used to form the prepreg into complex shapes prior to the autoclave cure process. The process is extremely slow and labor intensive and produces composite materials having optimum performance-to-weight ratios. Examples of the physical properties achieved by aerospace materials and processes are shown in table 1. When cost is considered, it is often two orders of magnitude or more above the cost of more conventional materials made by processes amenable to the mass production of products such as automobiles.

The area of surface materials in automotive applications will continue to be very competitive. If steel is to eventually be displaced as the surface material in future vehicles, there must be reductions in the cost of the raw materials, or higher productivity manufacturing processes must be developed. If this does not happen, application of plastic panels for exterior surfaces will occur only if the customer perceives some benefit and is willing to pay the additional cost.

Table 1. Aerospace materials

Material	Tensile strength (kpsi)	Tensile modulus (psi)
Unidirectional Kevlar (Aramid) fiber reinforced epoxy	525	19×10^6
Unidirectional boron fiber reinforced epoxy	450	57×10^6
Unidirectional carbon (pitch) fiber reinforced epoxy	275	55×10^6
Unidirectional carbon fiber reinforced epoxy	225	20×10^6
Unidirectional E-glass fiber reinforced epoxy	140	5.7×10^6

Automotive structural composite materials must be cost effective and yet must have performance that is sufficient to provide design weights that are equal to or lower than alternative material choices. The wide selection of automotive structural composite materials is shown in tables 2 and 3. Processes which are utilized for these materials are rapid and capable of producing components which integrate several components into a single piece. Part integration is critical in competing against low-cost alternative materials, such as steel and aluminum, because it enables the higher raw material cost of composite materials to be offset by reduced tooling and assembly costs, thereby allowing production of low volumes at reduced investment and assembly costs.

From table 2 it is apparent that there are several potential materials at the lower performance end of the strength and stiffness spectrum. These materials tend to be ineffective for higher performance structural applications due to the weight of an adequate design and also due to the cost of the material required. Another group of materials (see table 3) demonstrates higher levels of performance. These materials offer the potential to be cost-effective automotive materials, but their application in volume applications will require extensive processing development and demonstration of process capability. Part of this demonstration is to determine the level of physical properties attainable when rapid automotive processes and automotive reinforcement materials are used, as well as a comparison of potential material properties to design targets.

Table 2. Low-performance automotive materials

Material	Tensile strength (kpsi)	Tensile modulus (psi)
SMC-R50	23.8	2.27×10^6
HMC	26.3	2.13×10^6
AZDEL	16.5	0.9×10^6

Table 3. High-performance automotive materials

Material		Tensile strength (kpsi)	Tensile modulus (psi)
0.90 Promat		37.9	2.00×10^6
XMC		83.0	5.00×10^6
C20Rc30	0°	40.1	2.68×10^6
	90°	15.7	1.46×10^6
C10Rc40	0°	35.5	2.08×10^6
	90°	19.3	1.56×10^6
C40Rc20	0°	70.1	3.67×10^6
	90°	10.0	1.38×10^6

3. Limits and Needs

Today's RTM technology has some significant limitations, particularly in the area of cost-effective materials and processing technology for high volumes of components. Developments which will enable the production of higher volumes of components at costs competitive with alternative materials will be required prior to the further extension of this technology into the commercial marketplace.

3.1 RTM vs. S-RIM Resins

Preform and flow limitations are possible deficiencies of the S-RIM process; however, there are also several positive factors where S-RIM exceeds the capabilities of RTM. Due to the highly reactive nature of the resin systems available for use in S-RIM, cycle times for this process are currently faster than those for RTM. S-RIM resins also build viscosity rapidly enough that they do not normally flash out of the parting line of the mold enough to require additional sealing beyond a metal land area or pinch-off around the perimeter of the part. Mix ratios of S-RIM resin systems are near to 1:1 in volume, making them ideally suited for an impingement mixing process using an automated self-cleaning mixhead for injection.

3.2 Design Flexibility

Composite materials improve an engineer's flexibility in new designs in two ways. First, composite materials, and more specifically RTM molded composite materials, allow shapes to be formed that are difficult or impossible using alternative forming methods. The integration of multiple components provides a level of integrity not found in an assembly of multiple parts. In addition, the reduced number of tools and assembly fixtures required when forming an RTM structure enable a design to be tailored to a number of different market segments with a lower level of investment in plant and equipment. RTM composite structures may prove to be the only cost-effective way to manufacture low to medium volumes of some large, complex structures.

3.2.1 Size The RTM process is well suited to the manufacture of parts of various sizes. To date, large components with limited areas of intricate detail are more suitable for processing by RTM. Ribbed structures or bosses are difficult to preform, and once the reinforcement is preformed, loading a rib or boss preform into the mold requires extra hand labor or complex tooling slides. Tiny details such as grooves or slots for assembly are difficult to mold in. While not currently as well developed as RTM of large structural parts, small intricate components requiring precise location of reinforcement materials can be molded for applications where high-performance requirements preclude a process such as long-fiber injection molding or filament winding. Medical and space applications are examples of such small components.

3.2.2 Geometry Large, high-performance components with a large degree of part integration are ideal for the RTM process. Certain shape and design requirements must be observed for the process to attain its full potential for rapid, cost-effective production. A critical consideration in designing the shape of an RTM component is the joining and connectivity of the reinforcement materials. Any area where two pieces of reinforcement are joined must be adequately connected, or bridged, to allow acceptable load-carrying capacity to be maintained. While alternative processes such as SMC and thermoplastic stamping cannot provide the precise placement of reinforcement and high levels of physical properties provided by RTM, both processes minimize the need for concern over connectivity and reinforcement joints. Connection of reinforcement is most troublesome for cut-and-sew type preforms or preforms formed by filament winding, braiding, or knitting.

3.3 The Need for Preform Design Tools

Predictive tools for the design of preforms and the relationship of the preform structure to performance do not yet exist. Computer codes which go well beyond classical laminate analysis will be needed and must be developed to interface with other design codes used in part design. Outputs from such codes must help define fiber orientation in three planes, performance, preform shape (or in the case of preform stamping, blank shape), and binder design.

Additional efforts are needed to address connectivity between separate preform sections. Today a laminate approach, i.e., patches over seams, is used to give the preform structurally sound joints. Future preforms would ideally be applied as a unified form to the core or directly into the mold. If multiple pieces are used, a faster more reliable joining technique will be required.

3.4 Capabilities of RTM Tooling and Equipment

RTM resin systems tend to remain low in viscosity during the injection process; thus the use of slides and ejectors must be minimized or avoided. Sealing of slides and ejector pins is being evaluated by several resin suppliers and part producers, but to date there is no proven high-volume system using slides in operation. Resins used in SMC or thermoplastic stamping are higher in viscosity at the time where full pressure is applied to the resin in the sealed tool; thus there is less tendency for resin leakage and resultant flash buildup around inserts and ejectors with these processes.

It is possible to avoid "O"-ring seals in some applications by using shear edges to seal the tool. Where shear edges are used, design compromises with respect to radii on edges at the surface met by the shear will be required to prevent "knife" edges on tooling surfaces resulting in some square corners on the part. The acceptability of square corners and resultant stress concentrations must be weighed against the cost and durability issues of using other means of sealing the tooling. The same problem exists in other composite molding processes; however, the components are generally two-dimensional in nature in processes such as SMC or thermoplastic stamping, making the use of shear edges or metal to metal seals easier. An additional benefit of using shear edges where feasible lies in their potential use to trim the reinforcement preform to size as the mold closes.

Gating and venting of RTM molded components can generally be accomplished after the part is designed through runner systems in the tooling and proper orientation of the part in the tool. It is, however, good design practice to consider both resin inlet gating and venting of air trapped within the closed tool during the initial design of the component when a production tool is desired for rapid cycle times. The low viscosity of the resin in RTM tends to make complete displacement of trapped air in a component more difficult than in other processes. The flow front advances rapidly and often becomes very uneven due to varying preform permeability within the mold cavity. Flow of the incoming resin must be properly regulated, and venting of trapped air must be accomplished at proper locations to insure a completely filled component. Gates and vents can be placed where designed in low-volume or prototype moldings through the use of tubes, drilled holes, and grooves in the tool or preform core. In a volume production tool, gates and vents must be self-cleaning or accessible for easy clean-out.

3.5 The Need for Improved Material Systems

RTM in its current state of development is best suited to components requiring only structurally sound surfaces having a good general appearance quality but not automotive Class-A quality. The closed mold nature of the process provides good thickness control and two finished surfaces, but when standard engineering resins are used with structural reinforcement materials, surface porosity and shrinkage marks are normal on the surface. With most structural molding resins, ribs, cores, and bosses will "read-through" and require specialized design techniques to minimize their appearance on the finished surfaces where Class-A is required. Work with low shrinkage resin systems and differential tool heating to force cure from one side of the part are improving the surface of RTM components significantly. Gel coats can provide Class-A surface, but they tend to slow the cycle time and require proper design of the backup laminate to eliminate read-through. Molded-in color and textured surfaces are both attractive capabilities of the process which could be used to enhance the appearance of structural components.

3.6 Economic Factors

For structural composite materials to gain increased use in the automotive and commercial sectors of the materials market, they will have to provide a cost/performance benefit equaling or exceeding the benefits provided by alternative materials. Current materials systems are, in general, too expensive for the performance they provide. Improving material system capability seems to be the most logical direction in which to proceed. This, coupled with improved manufacturing and design capability, may ultimately provide structural composite materials that can compete with metals in high-volume applications.

3.6.1 Material Costs In most moderate- to high-volume applications of RTM (i.e., 10,000 to 50,000 units) material costs will be a dominant factor. Resins for RTM are similar in cost to those used to formulate SMC materials, ranging from $.50 per lb. range for general-purpose polyesters to $1.00 to $1.50 per lb. for the higher performance resin systems such as vinylesters. Fillers are not normally used in RTM or are used sparingly; thus the overall resin cost of an RTM component will be higher than SMC on a pound-for-pound basis. RTM resin systems are generally less expensive than thermoplastic resins used in stamped thermoplastic systems given equal strength and stiffness requirements.

Reinforcement materials for RTM are initially equal in cost to those used in other molding processes. Additional cost is normally incurred as the reinforcement is processed into a preform having the desired fiber orientation for a given application. SMC and thermoplastic stamping also have processing costs associated with forming the resin and reinforcement into preimpregnated sheet materials. Where simple preforms, such as die-cut random-mat materials, are used, costs are near those of SMC. For more complicated preforms using oriented engineered fabrics, braided or knit reinforcement materials, reinforcement costs will be higher. Although costs for resin and reinforcement in the RTM process may exceed material costs for SMC and thermoplastic stamping, the higher performance and increased ability to fabricate large, more highly integrated structures will often offset the material cost differential.

Scrap costs can be significant when high-performance resin systems and reinforcement systems are used. Typical low-volume RTM practice eliminates excess air in the mold by flowing large quantities of resin through the mold to flush out trapped air. This practice, while acceptable for prototype applications, results in unacceptable quantities of scrap resin. Developments have been made in S-RIM systems which virtually eliminate any excess resin use through careful control of inlet gates, flow front movement, and controlled venting of the mold. Similar developments must be investigated for RTM systems which will minimize resin scrap.

Currently, the cost of scrap reinforcement can range from very low values in a cut-and-sew preform using fabric, where little material is wasted, to around 30% to 40% for a stamped preform of complex geometry, where large amounts of material must be trimmed from the perimeter. Increased conformability in the reinforcement sheet used for stamping, combined with improved binder technology (i.e., how the sheet is held during the stamping operation to prevent wrinkling or folding of the reinforcement), will likely reduce, but not eliminate, scrap in the stamping process. Some alternative processes such as SMC and thermoplastic stamping have minimal scrap because precut charges are designed to fully utilize the prepreg material. Once again, it should be apparent that if the unique benefits of RTM are not being fully utilized to offset the higher scrap costs, alternative processes will normally be less expensive.

Recycling scrap material from the RTM process is relatively easy because the resin and glass scrap material are separate. The value of the scrap materials is currently low, and a potential market for them has not been developed.

3.6.2 Equipment Costs The ability to readily and inexpensively manufacture realistic prototype designs using RTM is a major economic advantage of this process. The low pressure required and the availability of room-temperature curing resin systems allows the inexpensive fabrication of prototype. An additional benefit lies in the accuracy with which the prototyped components tend to simulate the physical properties of production molded components. Processes such as injection molding and thermoplastic stamping require large presses and high-quality tooling to adequately simulate production components. SMC can be duplicated with lower pressures, but often physical properties are not adequately simulated. In any case, formulation of the required SMC prepreg material or adequate quantities of injection molding pellets presents a major expense.

The equipment needed to prototype an RTM component can be as simple as an epoxy tool clamped together by a small air bag press or mechanical clamps. Resin injection is normally accomplished using a small pressure-pot system or low-cost resin transfer pump system. Simulation of some S-RIM systems may be complicated by the highly reactive chemistry, but most systems can be slowed down adequately to allow prototype molding. Foam cores and a full range of reinforcements can be used in the prototype process with no sacrifice in physicals available from a production set-up. RTM is being used in a small number of moderate production applications, but truly high-volume applications are limited. Depending upon volume, production equipment will consist of presses and resin injection equipment similar to prototype equipment where low volumes are required to fully automated high-speed presses and injection equipment for automotive quantities. If low volumes are required, RTM offers particular advantages with respect to equipment costs. Higher volume applications of RTM require presses equal in platen area to SMC and thermoplastic stamping presses but with much lower tonnage. Additional cost for RTM resin management equipment will be offset in most cases by the additional expense of higher tonnage equipment required for processes such as SMC. The operating cost of presses is generally a function of tonnage; thus lower tonnage presses will incur lower operating costs.

3.6.3 Tooling Costs Tooling for production RTM can also cover a range of materials dependent on volume level. Low volumes can often be molded using epoxy tools. Epoxy tools may be easily damaged, particularly during the preform loading phase of the molding cycle, and if the part is complex or the reinforcement content is high, the number of parts that can be molded in an epoxy tool may be very low. Automotive quantities of production will likely require steel tools similar to SMC tooling or injection molding tools. When production levels are in the 10,000 to 50,000 unit level, sensitivity to tool cost is low and the durability of steel is required. Steel or zinc cast tooling may be required for some rapid curing resin systems because of their heat transfer capability.

RTM offers a higher potential for part integration than is achievable with other competing forming processes such as SMC or thermoplastic stamping. The capability of the process to incorporate closed-box sections, molded-in inserts, and multiple types of reinforcement materials, when combined with process attributes such as low forming pressures, the ability to form deep sections with minimum draft, and the suitability of the process for forming large components, results in the flexibility to integrate a large number of smaller components into one large RTM part.

3.6.4 Preforming Costs Preforming of the reinforcement fibers into complex geometries is currently the most expensive and least developed area in the RTM process. Although it is possible to mold more complex structures as a single piece, the cost of preforming increases with complexity. SMC may be a better choice for a product of moderate size and performance which can be formed easily using compression molding. Large, simple shapes where preforming is inexpensive and large, complex shapes beyond the capabilities of SMC are logical applications for RTM.

3.6.5 Secondary Processing Costs In terms of secondary processing costs, RTM components tend to be less expensive due largely to the more integrated nature of the components, which require less assembly resulting in reduced labor and equipment costs. RTM components normally have a minimum of flash, and the flash contains little or no reinforcement which simplifies trimming operations. Reinforcement is located where it is required during the preforming process and remains in place during molding, resulting in performance that is engineered in and thus requires less nondestructive evaluation to verify the physical properties of the finished component.

3.6.6 Energy Costs The majority of the RTM process is highly automatable, being similar to conventional injection molding or SMC molding. Management of the reactive resin systems during the process is currently automated in some reinforced RIM operations. Loading the reinforcement preform into the molding tool can be automated in all but the most complex cases. Automation has not, as yet, been applied to preform manufacture in any complex component. A fully automated RTM system, including automated preforming, has yet to be demonstrated for a large, complex component.

Energy consumption is lower for RTM than for SMC or injection molding. The reactive nature of the resin systems used reduces the heat required for curing the molded part. Low-pressure clamping equipment results in lower power requirements for presses. The use of reactive thermosetting resin systems also eliminates the large heating ovens or heated molding barrels required when thermoplastic systems are injection or compression molded.

3.6.7 Foam Core Costs The capability of using foam cores is one of the most significant benefits of using RTM when part consolidation and complex geometry are required. There are, however, costs associated with the core in terms of the cycle time required for foam molding, added cost of the core material, and additional weight of the core in the structure. The core weight penalty can be significant when large closed sections are required, and injection pressures necessitate a high-density core material to avoid core collapse. Additional resin pumped into a part due to core collapse has historically been a severe economic problem. Proper core design can eliminate the problem if it is anticipated during the design process.

4. Material System Needs

There are several key areas in which improvements in materials systems would be of major benefit in advancing the state of the art in RTM. Many potential applications of composite structures proposed for near-term consideration would benefit from materials with improved resistance to moisture, more cost-effective preform methods, and foam cores with improved thermal stability.

4.1 Improved Environmental Resistance

The environmental resistance of composite systems has proven to be a critical design consideration [11,12] in that chemical attack lowers the tensile strength and also affects the tensile modulus of most glass-reinforced polymeric composite systems. While a multitude of automotive fluids, cleaning fluids, and chemicals encountered during operation of a vehicle must be resisted, humidity appears to be one of the most aggressive environments for the materials currently available. A more thorough understanding of the chemical degradation of the reinforcement/resin interface will first be required, followed by development of resin and reinforcement systems that will resist chemical attack and subsequent reduction in performance.

4.2 Cores with Increased Stability

One of the most novel and advantageous features of RTM is the ability to use molded-in cores in the design of a component. Core materials are typically foam but may be any material which provides the desired functionality while retaining its dimensions during the heat and pressure encountered during the molding cycle. For critical structures such as the automotive front end structure shown in figure 13 the ability to form a full structure without bonded joints is necessary for successful application of composites to this structure. This can be accomplished by the use of foam cores with a density of 4 lb/cu. ft.

The use of foam cores can affect the dimensional stability of a component. Instability of a foam core when it heats during molding will result in uneven wall thicknesses, residual stress in the final part, bulging and distortion of the part upon demolding, or all of the effects together. If foam cores are used, cycle times must be short enough to prevent the foam core from reaching a temperature above the maximum stable use temperature, or the foam temperature stability must exceed the maximum process temperatures. The use of foam cores to form three-dimensional sections provides specific design advantages for the RTM process; however, when foam cores are used, the molding pressures must be maintained below the level at which the foam is compressed. Some compression of the foam may be acceptable, but if significant compression

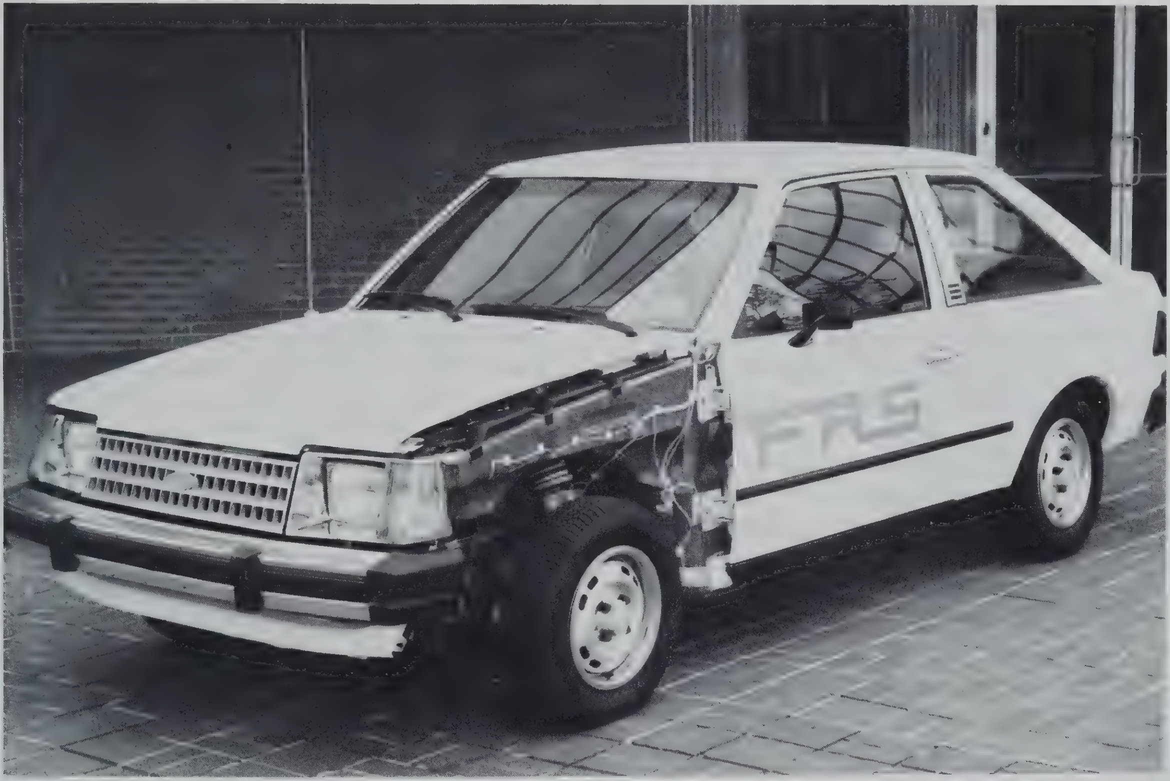

Figure 13. Structural composite Escort front structure.

occurs, a resin-rich area will be formed adding weight and cost to the component.

4.3 Improved Preform Technologies

Experience gained to date in a number of automotive structural composite programs [2,4] has resulted in a generalized set of attributes likely to be required of a preform process. Of primary importance is the capability to fabricate preforms to net shape. This must include a minimum of excess bulk in preform mass as well as a minimum of free reinforcement strands, both of which tend to interfere with loading and closing of a tool.

To be production viable, a preform must be easily handled manually or robotically. It should remain stable during storage at normal production plant conditions, including elevated temperature and humidity. Preforms currently available generally have a low tolerance to abrasion during handling, which results in a loosening of the preform structure and subsequent difficulty in loading the preform into the tool.

Economic considerations are critical in any envisioned composite application. Low labor content, rapid cycle times, and low material waste are all key features of an economical preform process. Ultimately there must be an optimization of cost versus performance of the composite structure which results from the preform. Such an optimization dictates that a preform process must be capable of utilizing the anisotropy of the reinforcement as well as varying thickness where appropriate. It is likely that any process will need the ability to use both random and directional reinforcement orientations to achieve maximum performance at minimum cost. While the optimization of cost versus performance is ultimately going to be a key requirement, there are near-term applications where some of the advantages of composite materials can be applied using less than optimal preforms.

5. Quality Control

Meeting well-defined quality and reliability targets is a requirement for any structural material, whether it is conventional steel or high-performance composite. The auto industry is certain to demand increased levels of quality over the next few years. Any potential fabrication process must provide demonstratable levels of quality and part-to-part reproducibility. Dimensional accuracy and variability, as well as reproducible values of performance from part to part, are required.

Traditional methods of quality control for composite components involve careful control of process conditions, reinforcement and resin quality, and thorough inspection of components. Control of such parameters as cycle time, molding pressure, mold temperature, and resin temperature will yield RTM components which are dimensionally consistent. The relationship of these variables and the ultimate precision with which large structures can be molded is not well understood. The lack of understanding stems primarily from the use of inexpensive tooling in most work done to date on large components. If the variability of incoming raw materials is measured, it is possible in some cases to predict the variability of the final product with respect to its performance. This tends to be true for properties such as density and tensile strength but is less feasible for attributes such as fatigue and impact performance which are more dependent on the resin processing, e.g., cure for thermosets or crystallinity for thermoplastics.

Inspection of the final product is difficult to implement for structural composites, but in critical applications inspection is currently required. X-radiography is often used to search for anomalies in fiber orientation. X-ray methods are expensive and difficult to analyze by automated methods.

Ultrasonic methods can be used to locate voids and resin defects and are particularly well suited for detecting small planar defects which are difficult to resolve by X-ray. Ultrasonic techniques, while accurate and more easily automated, tend to be slow and susceptible to equipment variation, requiring frequent calibration. A third method, which uses acoustic emission methods, may present the best alternative. The component must be instrumented with transducers at several surface locations and loaded by application of a force or thermal energy. A computer acquires the acoustic signature of the part and compares it to a set of standards. The drawback of this technique is a lack of correlation between acoustic emission and component performance for complex structures.

Inspecting each component is time consuming, requires expensive equipment, and results in the rejection of some components which are typically large and expensive. Engineered-in quality, sometimes referred to as intelligent processes, would appear to be a preferred technique for quality improvement and quality assurance. An intelligent RTM process would utilize sensors for measuring pressures, temperatures, resin velocity, and degree of cure. As data is acquired, a comparison is made with a predetermined set of nominal process values, and real time adjustments are made to compensate for process variability. Using this strategy, some degree of process and raw material variability can be offset by further real-time process changes, resulting in a more uniform product which requires less inspection and produces fewer rejected components. RTM is an ideal process for intelligent process control due to the "long" fill times, the resin vents and large tools normally used. Processes such as injection molding form a component in such a short time that there is insufficient time to acquire data, calculate process control data, and alter process conditions prior to the end of the forming cycle. RTM cycles are "longer." Six minutes is typical today; consequently actions such as altering catalyst concentration, opening or closing vents, or altering holding pressure can be accomplished fast enough to alter the component being molded.

It is unrealistic to rely on any one strategy to provide process control and high quality. A combination of controlling incoming raw material quality, intelligent process control, and selective inspection will provide the most cost-effective control of the RTM process.

6. Data Base and Testing

One of the obvious needs of the design engineer is accurate physical property data for the material system proposed for a design. Polymer composites provide a wide variety of tailored physical properties by varying the reinforcement type, reinforcement orientation, resin system, and processing techniques. A consequence of this variety of properties is the need for more specialized property data for a composite system. The composites industry is in its infancy in comparison to industries such as the steel industry. There are not common methods of uniform identification of composite systems which are analogues to metal identification standards. ASTM-D 4000 represents a step in the direction of more descriptive identification of polymer composite systems, but much more is required if the design engineer is to be confident when comparing material systems or substituting one material for another.

In addition to a unified material identification system, a well-defined method of obtaining physical properties for polymer composite systems is necessary. Tests developed for highly anisotropic aircraft materials (e.g., unidirectional carbon/epoxy composite) do not necessarily translate well for characterization of lower performance more isotropic materials. Often tab and sample geometry must be modified, and occasionally fixtures must be redesigned. Such a uniform test method for RTM molded composite materials with performance varying from high to moderately low levels is currently under development by the Automotive Composites Consortium. Properties such as tensile strength and modulus, Poisson's ratio, and compressive strength are well understood, and existing tests can be used to generate design data for RTM composites. Because RTM can be used to make very thick composite panels, samples for measuring third-dimension properties are more easily made than in processes such as compression molding.

Test methods which measure durability-related performance of material systems are less developed and provide data which is currently harder to factor into a design. Tests for fatigue, environmental resistance, creep response, and impact are much less standardized and provide data applicable to a specific application and operating environment. Standardized tests and the correlation of test data to composite performance are required for RTM composite systems.

Progress in composite implementation in structural applications is slow and has tended to be evolutionary. A well-developed expert system for storage and retrieval of research and production experience could help avoid redundant experiments and development that frequently occur once everyone who has worked on a specific application has moved on to other design projects (the "5-year cycle").

7. Resource Recovery

Although recycling of composite structures has not become a major issue due largely to the low number of structures being produced, an effective resource recovery strategy will ultimately be needed for large RTM components. RTM components normally have minimal filler content and some level of high dollar value reinforcement. The higher value of the raw material content may provide more incentive for development of recycling processes. Absence of filler in the system will provide scrap with a higher energy content and less residual noncombustible materials, possibly making RTM material more attractive for incineration.

8. Repair Technologies

Repair of composite structures presents challenges in several areas. First, identification of the damaged area and determination of the extent and degree of damage must be accomplished. Some slow and expensive processes exist for aircraft structures, but rapid methods which are cost effective for vehicle repair are only in the developmental stage at present.

Once identified, damage repair techniques need to be perfected. Some RTM resins could be used in a hand-applied repair process, which may present a benefit when compared to compression molded or injection molded materials.

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Mr. Johnson has worked in the area of materials and manufacturing process development at Ford since graduating from Alfred University in 1969. He worked on the development of high-temperature ceramic materials for gas turbine engines and the development of fabrication processes for net shape ceramic turbine components. In 1979 he joined the newly formed Composite Materials Group within the Metallurgy Department. His responsibilities have included direction of material development and characterization as well as development of new manufacturing processes for large composite structures. He currently heads the Structural Composite Research Group within the Material Science Department of Ford's Scientific Research Laboratory.

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Class "A" Resin Transfer Molding

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An overview is given of materials and processing for resin transfer molding (RTM) class "A" components. Thermoset resins, gel coats, fillers, surface veils, preforms and reinforcements, initiators, low profile thermoplastic additives, and other materials used in RTM are described briefly. Processing equipment and steps, advantages and disadvantages of different tooling and their economics are reviewed. Several applications in automotive and truck markets are described. Future needs and opportunities for innovations are presented.

Key words: class "A" RTM; low-profile additives; low-shrink resins; preforms; resin transfer molding; RTM; thermosetting resins.

1. Introduction

The use of plastics in automotive/truck applications continues to increase for both structural and class "A" body panels. Class "A" automotive panels refer to painted exterior body parts with high gloss surface finish. Structural parts are, for the purpose of this review, all other reinforced plastic parts used in automotive applications. Until recently, sheet molding compound (SMC) composites dominated the thermoset market in the class "A" arena. Resin transfer molding (RTM) was introduced in the 1940's, although without much commercial success until exploited by Owens-Corning Fiberglas and others in the 1960's primarily for structural applications. To make an appearance part, extensive post molding operations such as sanding, filling the surface, priming, and refinishing were necessary. This slow and labor-intensive approach was limited to very low volumes and prototype applications. However, with the introduction of low-profile additives (LPA), this low pressure compression molding technique has found a niche of its own in the class "A" automotive/truck market. Today, it is possible to mold a class "A" appearance RTM part which requires very little post-molding and finishing. In the following sections a brief description of each process step and the materials needed will be given.

2. Processing and Materials

Resin transfer molding (RTM) involves several steps. Two mold halves are prepared in the usual manner. Reinforcement is cut to shape and placed in the mold. The mold edges are sealed, and the halves are mated. A predetermined amount of resin is pumped into the cavity and the material is allowed to cure. The mold is opened and the part is removed.

2.1 Generic RTM Process

Resin transfer molding (RTM) is a process that has been practiced for many years for the molding of composite panels. It is intended to be a low-volume, low capital investment process that yields a part with two good sides. Only in the last few years has this process been applied to molding appearance grade parts of sufficient quality to be used for limited production runs. A typical molding process for an appearance grade RTM part would be as follows:

a) External mold release is applied to the mold surfaces.
b) Surface is polished for maximum surface quality.
c) Non-"A" surface of tool (landed area) is masked off prior to application of gel coat.
d) Gel coat is applied to the "A" surface to the desired film thickness and allowed to cure to a semi-solid state.
e) Preform reinforcement is placed in the tool and trimmed to fit as required.
f) Mold is closed and clamped shut. A predetermined amount of resin is injected into the mold and allowed to cure.
g) Mold is opened, part is stripped from tool, and the process is repeated.

2.2 Low-Profile Resins

Development of low-profile additives (LPA's) for use in RTM resins can be considered the single most significant breakthrough in promoting the use of this process in class "A" applications. Low-shrink resins are a combination of a liquid thermosetting type such as a high reactivity polyester, and a finely dispersed or dissolved thermoplastic low-profile agent. The latter may be polyethylene, polystyrene, polymethylmethacrylate, copolymers of styrene, copolymers of methacrylates, polyvinylacetates, polycaprolactones, PVC, cellulose acetate butyrate, cellulose acetate propionate, and others. Epoxy resins have been used in class "A" RTM applications and offer good mechanical properties with reasonable surface quality but at a premium price. Vinyl esters have also been used in some applications at a moderate price, with properties in between epoxies and polyesters. The resins are sold as either a two-part system or a one-component system.

Several suppliers are actively engaged in developing class "A" resins. Notably, Ashland Chemical Company has been engaged in developing a one-pack polyester resin system for use in class "A" RTM applications. Freeman Chemical, ICI, Amoco, Dow Chemical, and others offer a variety of RTM resins. Several custom molders, including GenCorp Automotive, have focused on the development of a production worthy process. A key requirement in processability of an RTM resin is low viscosity: typically under 500 cps during mold filling. This is necessitated by the low-clamp pressures and corresponding low-injection pressures used in RTM. The resin must be compatible with the sizing on the reinforcement to ensure good wet-out.

2.3 Catalysts

To date, only low-temperature catalysts have been used in class "A" RTM resins in order to avoid damaging the epoxy tools, which cannot withstand sustained exposure to temperatures higher than 200 °F. The most common catalyst used is MEKP in combination with cobalt accelerators and tailored for the desired molding temperature and reaction rate.

2.4 Fillers

Fillers are used to extend the use of resin, improve surface quality, and help with dimensional stability and stiffness. Calcium carbonate is the most common filler. However, alumina trihydrate and glass bubbles, as well as other fillers, have been tried.

2.5 Preforming

One of the basic components of an RTM composite is the reinforcement used to improve the physical and mechanical properties of the composite. The reinforcement can be material such as carbon fiber or fiber glass in a variety of forms such as continuous strand mat, woven roving, chopped strand mat, unidirectional cloth, or continuous strand roving. For relatively flat and low-volume applications, these materials are often hand cut, fitted, and placed in the mold. With complex shapes and higher volume applications, a more efficient means is needed: preshaping the reinforcement to fit the mold. The processes that currently look most attractive for making preforms are addressed here.

Preforming with gun roving is a process that has been used in the FRP industry for many years. A directed, chopped fiber preform utilizes an air-assisted chopper/binder gun to convey a mixture of chopped glass and binder onto a perforated metal screen, identical in shape to the part to be molded. This mixture is held on the screen by vacuum created in the chamber behind the screen. After the required amount of glass and binder has been deposited on the screen, the screen is rotated in a ferris wheel-like fashion into an oven, where the preform is allowed to cure and set. After the preform is sufficiently baked, the chamber is again rotated and the finished preform is removed. The advantages and disadvantages of this process are:

a) Material costs are kept low by the use of continuous strand gun roving.
b) Material utilization is reasonably high.
c) Process is highly operator dependent in material build-up which affects physical and mechanical properties. If cost justified, a programmable robot may be used to spray the roving.
d) Environmental impact of operating this type of preform must be carefully considered, as a large quantity of material is being sprayed and a large volume of air make-up is required to offset the vacuum.
e) Preforming can be done independent of the molding operation without using a compression press.

Thermoformable glass mat with a thermoplastic binder can be heated and pressed into a preform. This process is still in the development stage. A typical operation consists of a fiber-glass mat cut to a predetermined size that is placed into a stretcher frame and clamped about its perimeter. This material is then heated to approximately 300 °F using infrared heaters or hot air. Upon reaching the required temperature, the material is pressed in a preform mold made to duplicate the part shape and using 50 psi or less pressure. In order to assure a well-defined preform, this operation has to be accomplished in less than 10 seconds from removal of the heated blank mat to the closing of the preform mold. The preform is pressed into shape when the mold is closed. The thermoformable mat is allowed to cool and set in the preform mold. The mold is then opened, and, after the preform is removed and trimmed as necessary, it is ready for use. The advantages and disadvantages of this process are:

a) The glass is distributed uniformly, and extra reinforcement is easily added locally.
b) Surface veil can be formed with the thermoformable mat and held in place by the binder from the mat. The presence of the veil should yield a smoother surface.
c) High waste is common depending on part shape and complexity.
d) The cost of the thermoformable mat is high.
e) A preform mold and press time are necessary to make the preforms.

The third method of producing preforms is very similar to that just described except the binder is a thermosetting resin. It is sprayed on glass mat and baked in a separate operation. This essentially leaves the material in an uncured “B” stage. The manufacturing process is also very similar except for the level of heating required, which is reduced to approximately 180 °F. All other features and pros and cons are similar.

2.6 Purpose and Function of Surface Veils

When molding with a mat, as is the case of RTM, some readout of fiber patterns will occur on the surface of the part unless some corrective action is taken to mask this phenomenon. A widely practiced solution is to use a surface veil on top of the reinforcing fibers. The surface veil is a finespun layer of either glass or polyester that creates a resin-rich layer on the top surface. This resin barrier is intended to prevent the fibers from printing through to the surface, which is essential to a class “A” finish.

Surface veils come in a variety of forms dependent on the particular needs of the application. Veils can be made out of either polyester or glass, with thickness ranging from 0.005″ to 0.025″. Special features can be added to the material to make it conductive, a special color, or even a unique pattern imprinted on the veil that will appear conversely on the surface of the molded part.

2.7 Gel Coats

Gel coats are used to improve the surface finish of the molded part by sealing the surface porosity and providing a hard surface coat which can be sanded and painted to achieve a quality finish on the “A” surface. A gel coat is a specially formulated polyester resin with thixotropic agents, fillers for flow properties, pigments for color, and additives for specific properties dictated by the application.

A gel coat is usually applied with a spray gun having large orifices (for passing through the viscous material) and several sets of atomizing orifices for positive breakup of the gel coat material. A film build of typically 0.018″ thickness wet is applied to the “A” surface of the tool in several passes that are applied back-to-back. Film build thickness is critical to applying a good gel coat. A low film thickness will result in insufficient cure and allow the resin to attach and break through the surface, while a too high film thickness will be prone to flex cracking and surface crazing.

Special characteristics which can be formulated into the gel coat material are carbon black fillers to make the surface conductive (necessary for conductive paint systems) internal mold releases that allow the finished part to be demolded more easily, fillers to enhance sanding characteristics, pigments for the desired color, UV stability, and additives to improve physical properties in terms of heat deflection and flex strength.

2.8 European High-Volume RTM Process

There are several manufacturers in Europe using RTM for large-scale production. One is currently producing body panels for an all-purpose vehicle (mini-van), which has been in production for several years in its current form. Tooling for this program consists of nickel shell/epoxy backed molds heated with hot water to approximately 120 °F, with manually operated secondary drilling and trimming. Molds are handled by a hydraulic lifting mechanism that lifts the core half of the tool for part removal and cleaning, while tool clamping is accomplished by perimeter-mounted hydraulic clamps. A typical molding sequence is as follows:

> The glass mat is draped into the cavity half of the tool, and the mold halves are brought together and clamped. Resin is injected into the tool through several points simultaneously and allowed to cure (approximately 7 minutes). The mold is then opened, and the cured part is stripped from the cavity. These parts are not gel-coated but are extensively sanded and primed prior to shipment. By using heated tooling and some degree of mechanization in the processing, a relatively high volume of production can be achieved (for RTM) under the right conditions. Annual production for this vehicle has grown to over 30,000 units; hence, a decision was made to convert to SMC for the next generation vehicle.

2.9 Lotus VARI Process

Lotus Cars of Norwich, England, has patented a process for molding RTM body components which are used in both exterior and structural applications. The Lotus Esprit and Excel models are produced from two major components, a topshell and an undertray which are molded separately and subsequently bonded together to form a complete body unit. The recently introduced Elan is produced from one major component, the undertray, to which smaller panels, again both external and structural, are bonded to form the complete body unit.

The prime ingredient in the Lotus Vacuum Assisted Resin Injection (VARI) process that distinguishes it from other RTM processes, is a vacuum system used to hold the tools closed and to assist the resin flow through the tool. A typical molding sequence is as follows:

> The mold release is applied to the core and cavity and lightly buffed. Gel-coat is sprayed on the "A" surface of the cavity and allowed to dry. Glass reinforcements are then placed into the cavity half along with necessary core materials (parts are molded as one-piece constructions rather than separate inners and outers). The core half of the mold is lowered into the cavity, and a vacuum is applied to draw the two mold halves together. Resin is injected into the mold through fill port(s) and then allowed to cure. Tools can be unheated or heated; heated tools considerably reduce the cure cycle. After demolding and machining, the parts are assembled in a bond fixture to form a complete body shell.

2.10 Process Equipment

One of the distinct advantages of the RTM process is the relatively low capital investment required for equipment to run the process. There are four basic categories of components: clamping apparatus; metering and dispensing pumps for the resin; secondaries for trimming, drilling, and routing of the molded composite; and either a preforming system or a method of cutting blanks out of reinforcement sheet stock.

For large class "A" surface molds, a mechanical means of opening and closing the molds in parallel and properly registered to each other is essential to insure proper handling of the tools and to lessen the chances of damage to the class "A" tool surface. The best way to do this is to mount the tools in a vertical acting press of sufficient structural rigidity to give parallel closing and to generate up to 150 psi clamp pressure. This clamp pressure may be generated by using either an air or hydraulic based system. An alternative to using a press would be the mold perimeter clamps described earlier under the high-volume European process.

A key component of a successful RTM operation is an accurate metering system for dispensing the catalyzed resin mixture into the mold. The system must be capable of repeatedly measuring out the required shot size with the correct ratio between resin and catalyst. A common system for achieving this is a pneumatic driven reciprocating pump with a second cylinder slaved to the main cylinder for metering out the catalyst. Ratio adjustment, which will always be necessary because of the variety of materials and conditions practiced, is accomplished through mechanical adjustment of the linkage connecting the main pump (resin) to the secondary pump (catalyst). An alternate process that is starting to gain acceptance is a hydraulically driven rotary pump. This unit features two rotary pumps mounted on a common carrier and driven through an arrangement of gears by a hydrostatic motor. The volume of material dispensed is measured by electronically counting the number of revolutions that the pump has turned and equating this to a known volume per revolution. Ratio adjustments are made by a change in the gear ratio between the two rotary pumps.

Secondary fixtures for trimming, drilling, and routing the finished composite parts can vary widely. Parameters influencing the approach taken on secondaries are production volume, labor and overhead costs, equipment already in house, part size, and the variety of parts to be made. Sometimes a simple, hand-operated fixture is used where the part is dropped into a nest and clamped, upon which the operator would then perform a variety of hand operations using routers, drills, saws, etc., to finish out the part. At the other end of the spectrum, one may employ a sophisticated and programmable multi-axis robot equipped with a water-jet cutting head that automatically completes the trim operation.

Preforms are not required for many applications where draping the reinforcing mat or cloth can easily cover the tool surface. However, using preforms will help to insure a more uniform distribution of the fiber reinforcement and better lend themselves to an efficient production operation. Types of preforms and necessary equipment were discussed in section 2.5. The alternative to preforms is to accurately cut fiber reinforcement into shapes which have been developed through trial and error to properly fit the mold when it is closed and prevent unwanted voids in the reinforcement. Once a pattern is developed, a permanent set of templates is created from which all the production pieces will be cut. An improvement upon this process, if it can be justified economically, is to have a steel rule die created from which the fiber reinforcement blanks are stamped out in a press.

Beyond this, a variety of auxiliary systems will be necessary to support the process depending upon individual situations. These may include such items as heaters for heating the molds, gel-coat application equipment, electric shears for cutting the reinforcement, an oven to post bake parts if necessary, and a variety of analytical equipment to measure and insure proper operating conditions.

2.11 Tooling

Tooling used in molding class "A" surface composites is a critical item in determining the success of the program. It is tooling that gives RTM an economic advantage over other processes such as the expensive progressive dies required for steel stamping, or the high-strength molds capable of running upwards of 10,000 psi molding pressure locally as required for SMC. In contrast, molds for RTM can be constructed at 5%–50% of the cost of steel molds in several months instead of 9 months or more, which is usual with automotive exterior part molds. The type of tooling needed will be dictated by these parameters and by the anticipated annual volume, the life span of the program, and the quality of the surface desired. There are several types of tooling currently being used for RTM production: epoxy/polyester laminates with a back-up structure, nickel-shell construction, cast and machined aluminum, and steel.

The most commonly used tooling is the plastic laminate construction because of its relative ease of construction, its low cost, and the speed with which it can be constructed. The typical construction involves starting with a model of the surface to be molded. Upon this tooling aid the laminate will be constructed, starting with a surface coat that is sprayed onto the model. The surface coat provides a hard, porosity-free skin to the mold. The quality of its application and the model surface are critical in determining the surface of the finished composite which will be molded in the tool. The next step is to laminate a layer of resin and glass cloth or woven roving. This is followed by a layer of resin typically filled with metal shot or aluminum nodules. If heat lines are to be imbedded in the tool for controlling the tool temperature at something other than ambient, these would be layered in at this time and totally encapsulated. This completes the laminate portion of the mold. In order to ensure rigidity of the tool, a backup structure is then added to the laminate. This can be as simple as an egg-crate structure of wood or as complicated as a welded steel space-frame attached to the laminate. Once this half of the tool is constructed, the mating half is built in a similar manner by waxing off the first half (wax sheeting is applied to the surface to achieve the desired part thickness) and then building up the laminate and back-up structure as described above.

Generally, a plastic laminate construction would be recommended only for low-volume applications and prototype quantities which do not require high temperature (over 180 °F) molding for class "A" surface composites. Surface quality and durability are the limiting factors.

Nickel-shell tooling starts in much the same manner. Again, a model of the composite surface is used as the initial building block. Laminate constructions similar to those described above, but of a lighter construction, are fabricated. These tooling aids are then used to fabricate a plating mandrel. The plating mandrel is a specially made laminate construction that will be placed in the plating tank of nickel to form the nickel shell (must be compatible with plating tank chemistry). The tooling aids are used to fabricate the plating mandrels instead of the model itself in order to obtain the proper orientation of the surfaces. The mandrels are placed in the plating tank of nickel, where they are electroplated with nickel to a nominal thickness of 0.100″ to 0.300″ (0.250″ is the target). Heating lines, if required, are attached to this shell and then the back-up structure. Back-up structures are either a steel space-frame construction, steel plate egg crate, or a steel perimeter with an aggregate back fill. Excellent surface finish can be achieved with a nickel surface, but, again, this is dependent upon the surface of the model used and the surfaces generated through the tooling aid and mandrel process. The use of nickel shell tooling for class "A" composites is a relatively recent development, so a lot of questions are left to be answered as to its performance; however, early indications are positive.

The use of either aluminum or steel for RTM tooling is somewhat limited at this point. Aluminum and steel both represent a substantial increase in tooling cost over the previous options, which defeats the low-cost tooling advantage of the RTM process. In addition, the capital cost associated with handling these tools goes up proportionally. Steel has been used for experimental molds where surface quality is of the utmost importance (polished and chromed) but for little else in RTM. The use of aluminum is hampered by its inherent porosity, which is difficult to eliminate when polishing the mold surface to achieve a high gloss and correspondingly high quality in the molded part surface.

3. Applications

True class "A" RTM technology using low-shrink resins is still in its infancy. New and more complex applications are expected in automotive and truck markets as materials costs come down and process capability is enhanced. Other factors favoring RTM include design and styling flexibility, parts consolidation, large and complex shape molding, one-piece construction, insert and core capability, low-cost and quick turn-around tooling, low capital investment, localized and multiple reinforcement capability, light weight, corrosion resistance, etc. Typical tooling costs for RTM range from half to as low as 10% of the corresponding SMC tools.

The principal advantage of designing with composites is the ability to "engineer" optimal properties into the structure. If stresses are larger in one direction than another, the designer places a larger amount of the reinforcing fibers in that direction. However, the manufacturing steps needed to achieve these arbitrarily specified fiber distributions and orientations are generally expensive and slow. No process can offer more flexibility to achieve this goal at the most economical cost than RTM! By using different types of reinforcements such as carbon and glass fibers, chopped glass and woven mat, or other combinations, one may achieve localized stiffening and strength. Both part thickness and the amount of reinforcement can be varied throughout the part to meet specific performance requirements where needed. Inserts and cores can be virtually any material depending on the desired end results. Balsa wood, foam, steel, thermoplastic and thermoset components, and others have been used successfully. Removable cores such as sponge glass and high-temperature wax as well as inflatable bladders have also been used. Typical mechanical properties for RTM composites can vary significantly depending on the amount and type of reinforcements and resins used (figs. 1 and 2).

Current class "A" RTM applications include the Renault Espace mini-van, BMW Z-1 hood and deck, removable hardtop for the convertible Corvette, Lotus Esprit, Excel, and Elan, a limited edition Corvette hood, Pontiac GTA deck lid,

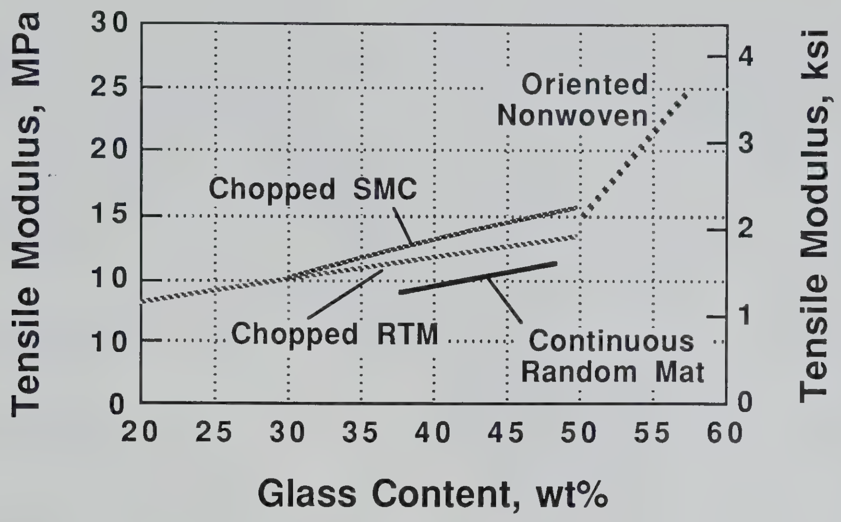

Figure 1. Tensile modulus of various RTM materials with E-glass reinforcement.

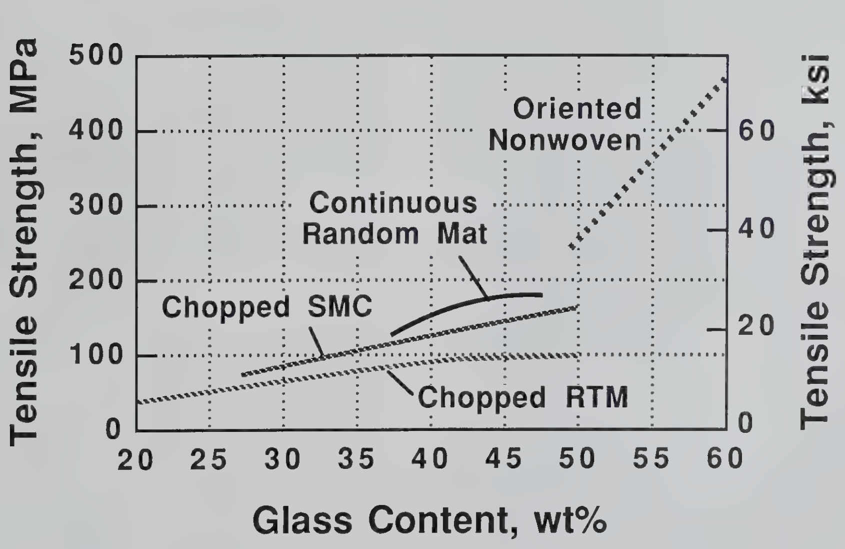

Figure 2. Tensile strength of various RTM materials with E-glass reinforcement.

Ford LTL 9000 truck, and a variety of prototype parts. Chrysler is considering the RTM process for its Dodge Viper sports car.

4. Future Needs and Innovations

In order for class "A" RTM composites to advance to their potential, a wide range of technological developments and innovations must take place. These improvements should not be limited to the manufacturing process but encompass materials chemistry, preforming equipment, tooling, secondary operations, and all associated hardware as well as design and applications.

In the area of materials chemistry, resin systems currently available for class "A" RTM composites are very limited. For a resin system to be used in this application, it needs to have appropriate low-profile additives in order to control the shrinkage of the material.

Although a currently available resin system has shown this to be achievable, much more is needed for enhanced success:

a) Low-profile additive stability: Shelf life of systems needs to be extended to provide a consistent part over a reasonable shelf life (60 days or better) at reasonable economics.

b) Mechanical properties: Flex strength, flex modulus, heat distortion temperature, tensile strength, and other properties need to be enhanced to levels comparable to those of class "A" SMC materials.
c) Surface quality: Gel coating is currently required to achieve a class "A" surface capable of going through a high-temperature paint oven system as is typically used in the automotive industry in the United States (temperatures ranging from 250–400 °F). A resin system capable of eliminating this expensive process step would contribute significantly towards promoting the acceptance of RTM composites and improving their economics.
d) Cure time: This is a direct function of the resin system's gel time for the specific size and geometry of the application. Gel time should only be slightly longer than the time required to fill the part completely. Curing to the point where the part can be stripped from the mold is typically anywhere from two to three times the gel time. In order for RTM to be a viable process for low- to medium-volume applications, cycle time for curing will have to be reduced through resin chemistry and process modifications that enable much faster filling, cross-linking, and curing. In addition, it is hoped that these improvements would also eliminate the current need for post-curing.
e) Resin catalyzation process: The ratio of resin to catalyst (A/B) for current systems varies anywhere from 3 to 1 to as high as 100 to 1. Consistent catalyzation at high ratios is sometimes hard to achieve and requires the use of a static mixer that must be flushed out with solvent after each injection. A one-part system that has been pre-catalyzed would eliminate this variation and the need for a static mixer. Molding temperatures would most likely have to be elevated in order for the resin to have adequate shelf life at room temperature.
f) Mold release system: Current molding of RTM parts requires the use of a mold release agent to assure adequate release of the part from the mold surface. At present, both internal and external release agents are used. A major problem with external release systems is the time required to apply and cure them, and, if the release is sprayed on, the airborne particulates will pose environmental concerns. The ideal solution is to use an internal mold release. However, currently available agents are at best only marginally effective. For RTM to become an effective production process, improved internal release agents need to be developed.

While not all of the items discussed above are essential for low-volume production of class "A" RTM composites, their incorporation will greatly improve the quality, economics, and reproducibility of this process, enabling higher volume applications. Economical preforming is another essential part of the RTM production process. There are basically two schools of thought on the type of process to be used to manufacture the preforms: directed sprayed-up and thermoformable mats. Both systems have their advantages and disadvantages, as discussed earlier. In the future, a directed spray-up system may feature horizontal orientation on the spray screen in order to take advantage of gravity flow for glass placement. Use of multi-axis robots is likely for applying the materials and to give the option of localized placement of special reinforcements. This could be an integral part of an in-line process of preforming, trimming, and loading of the finished preform into the mold. The result is a finished part being unloaded from the end of the line with no need for operator assistance throughout the production line due to the extensive use of automation and robotics.

Future systems for thermoformable mats are quite similar in concept in terms of a completely automated line combining the production of the preforms with the actual molding process (fig. 3). A major concern in using thermoformable mats is the cost associated with both the raw materials and the excessive waste currently experienced with this process. If these issues can be resolved, the thermoformable mat process has much potential for future use.

A third scenario which may occur is that both processes will be utilized depending upon part size, annual volume, complexity, and capital availability. Alternatively, some hybrid of the two processes that would combine the best features of both into one unit—such as spraying up the basic preform on a screen but then placing the preform into a mold to give it a well-defined finished form and combining it with a surface veil—could be utilized. The area of preforming offers many opportunities for development and is one of the essential keys to the commercial success of RTM composites. Potential developments in the manufacturing process that could promote the use of class "A" RTM include:

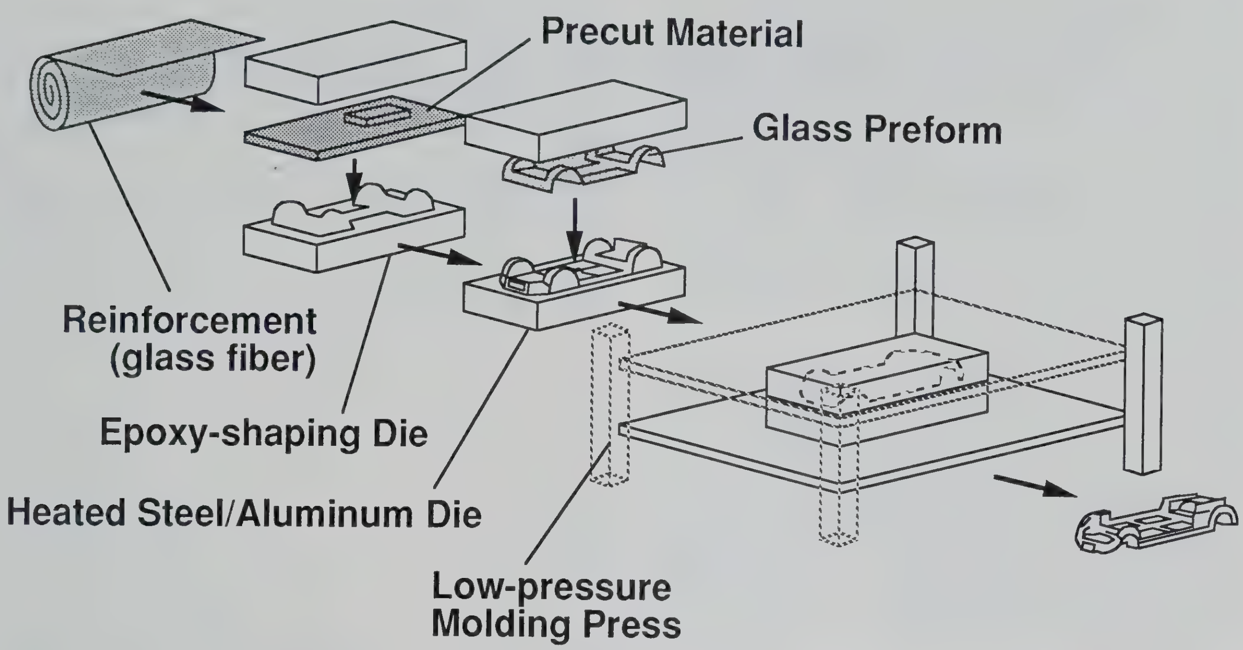
Precut Material
Glass Preform
Reinforcement (glass fiber)
Epoxy-shaping Die
Heated Steel/Aluminum Die
Low-pressure Molding Press

Figure 3. High-speed resin transfer molding.

a) Press: A shuttle bed press for clamping and using two sets of molds. The two tools are allowed to shuttle back and forth out of the press, alternating between molding in the press and preparatory work outside of the press.

b) Injection equipment: Equipment capable of injecting the resin into the mold cavity at high rate of flow without washing out the glass and metering out an accurate volume of material regardless of whether it is a one- or two-part system requiring catalyzation. Other features that might be incorporated are permanently mounted injector head(s), closed-loop control of injection, and integration of its control to a central manufacturing cell controller.

c) Vacuum assistance: The use of vacuum to assist in the filling of the cavity is already practiced by a few molders. Using vacuum would aid in drawing the resin through the glass, decrease porosity, and help to contain naturally occurring chemical fumes from the process.

d) Automated trimming: Inherent in any molding process is the requirement for secondary operations for part trimming, drilling and routing. For the low volumes typically associated with RTM operations, dedicated automatic tooling is not justifiable, resulting in many operations being done by hand. By using a programmable controller on an automated work cell featuring a multi-axis robot with either a water-jet cutting system or routing head, much of this manual labor can be relegated to a machine. By using a programmable piece of equipment such as this, one work cell can be programed to do a multitude of parts.

As discussed throughout this section on class “A” RTM, many opportunities exist for individual refinement and imagination. The RTM process has been around for many years, but only recently have strides been made to apply it to the production of appearance grade composites. This information is not intended to cover everything that is known on this subject but to provide a basis from which a reasonable understanding of the process and its intricacies can be gathered and applied. The reader is encouraged to seek additional details in the literature in areas of specific interest.

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Filament Winding of Reinforced Thermoplastics

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In-situ thermoplastic filament winding processes are presently in a developmental stage compared with thermoset technology. The differences between thermoset and thermoplastic filament winding are discussed, and the thermoplastic feed materials that exist today are reviewed. The state of the art for thermoplastic filament winding is examined, and conclusions are drawn from this open literature. Limitations and needs of the in-situ thermoplastic filament winding process are identified. These limitations and needs include process control, equipment, quality assurance, design, and data base. If these limitations are resolved, the economics will drive thermoplastic filament winding into a primary automated manufacturing process.

Key words: in-situ consolidation; in-situ filament winding; thermoplastic filament winding; thermoset filament winding.

1. Introduction

The filament winding process is a simple and economical method for producing axisymmetric parts. This process is one of the most widely used, automated manufacturing methods in the composites industry today. The art of filament winding can be traced back more than 30 years, with patents first appearing in the early 1950's. All of this early work was aimed at thermoset resin systems.

Filament winding is a process by which fibers are placed onto a mandrel in a predetermined path which creates a given shape or part. By combining fibers and resin during this process, a structure with unique properties can be manufactured. Current manufacturing techniques incorporate either thermosetting or thermoplastic resin systems.

In the thermoset filament winding process, a fiber is coated (either by prepregging or dip bath directly mounted on the winder) with thermosetting resin and wound onto a mandrel (fig. 1). As determined by part design, the wind angle (defined as the angle measured from the axis of rotation) is typically between 10° and 90° with respect to the primary axis, and the mandrels are axisymmetric in shape (e.g., pipe, rocket motor cases, pressure bottles). With more advanced computer-controlled equipment, nonlinear shapes (e.g., car door frames, pipe elbows) may also be wound.

After a part is wound, the composite must be cured using both heat and pressure to complete the chemical reaction of the thermosetting resins and to eliminate voids in the final part. This process typically uses a vacuum bag/autoclave cure, which can add up to 30% or more to the cost of the final part.

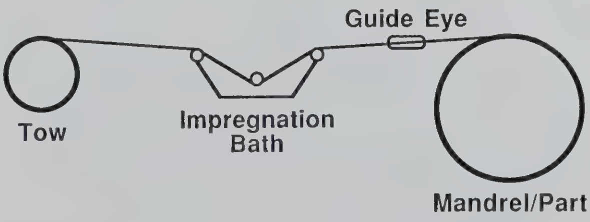

Figure 1. Schematic of a Thermoset Winding Process.

In the early 1980's, new fiber/resin systems were developed which incorporated the use of thermoplastic polymers coated onto fibers. With the advancement of these polymers and the processes to impregnate reinforcing fibers, the ability to consolidate the material (i.e., make a virtually void-free part) during filament winding and thus eliminate the post-consolidation step can become a reality. An example of the in-situ filament winding process would be to heat both the part and the tow and add pressure to consolidate the tow to the part (fig. 2). The result is a finished part which can be taken directly off the mandrel without the need for oven or autoclave consolidation. In many cases, this in-situ process gives thermoplastic materials a potential economic edge over thermoset systems without a reduction in material properties. In addition, this process offers the potential to eliminate of those defects typically induced during oven or autoclave consolidation.

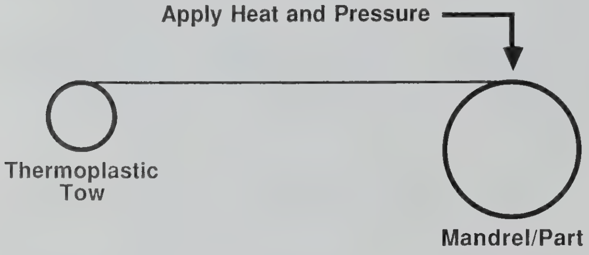

Figure 2. Schematic of a thermoplastic winding process.

Other advantages of thermoplastic polymers over thermosetting polymers include:

- Improved elevated temperature properties
- Improved damage tolerance
- Reduced processing time
- Improved shelf-life (indefinite)
- Potential to recycle scrap

1.1 Types of Raw Materials

The precursor or feed material used in thermoplastic filament winding consists of a fiber that has a measured quantity of thermoplastic polymer applied to it. Typical reinforcing fibers that are used for precursors include: carbon, glass, and Kevlar® aramid. Representative mechanical properties for these fibers are listed in table 1. A wide variety of thermoplastic polymers are available for impregnation, the most common are:

- Polyether ketoneketone (PEKK)
- Polyether etherketone (PEEK) (APC-2®)
- Nylon (J-2®)
- Polyphenylene sulfide (PPS) (Ryton®)

This list includes semicrystalline polymers (e.g., PEKK, PEEK and PPS) and an amorphous polymer (J-2®). Typical mechanical properties for these are given in table 2.

Table 1. Typical properties of reinforcing fibers

Fiber	Specific gravity	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation (%)
Graphite				
AS-4	1.8	3590	234	1.6
IM-6	1.82	5140	272	1.75
Kevlar®	1.44	3620	124	2.5
Glass				
E-Glass	2.55	3448	72	4.3
S-Glass	2.49	4585	85	4.8

Table 2. Typical properties of thermoplastic polymers (from Chang and Lees [1])

Polymer	T_m (°C)	T_g (°C)	Modulus (GPa)	Strength (GPa)
PEKK	338	156	4.50	102
PEEK	340	144	3.79	103
Nylon (J-2)	None	120	3.17	103
PPS	285	85	3.91	80

Until recently, quality thermoplastic tow was not available on the open market. Today the feed materials are available in the following forms:

- Melt impregnated tow
- Powder impregnated tow
- Commingled tow
- Solution coated tow
- Slit tape

Melt impregnated tow is produced by melting the thermoplastic polymer and applying it to the tow with coating and impregnation equipment. Typically, thermoplastic polymers have high viscosities and must be forced into the tow bundle with pressure. A powder impregnated tow is produced by opening the tow bundle (electrostatically or mechanically) and applying a fine powder of polymer to the fiber. This polymer can be melted in later steps to produce a consolidated tow bundle, or the outer surface can be melted creating a sheath/core tow. Commingled tow is made by combining a reinforcing fiber with a polymer fiber. The two tows are combined (mechanically or pneumatically) to create an intermingled tow bundle. In a solution coating process, the polymer is dissolved in a solvent, and the fiber is dipped into the solution and coated. The solvent is then driven off by heat leaving the polymer on the fiber. This process is very similar to a thermoset prepregging operation. The last form of feed material (slit tape) is produced simply by slitting a wide tape (typically 12″ wide) into narrow tows.

Several producers of feed stocks are listed in table 3. ICI, Phillips, and Du Pont have not published how they impregnate their tows, but their processes produce fully impregnated feed stock. Thermoplastic Composites and BASF produce a commingled tow which is not fully impregnated. Each of these feed stocks has its own advantages and disadvantages (listed in table 4) and each will find its own niches in the marketplace. In selecting

Table 3. Producers of feed stocks

Supplier	Material	Comments
ICI-Fiberite[a]	PEEK/Graphite	High Temp Performance (150 °C) Excellent solvent resistance High impact strength/good damage tolerance Good flammability characteristics
Phillips[b] Petroleum	PPS/Graphite PPS/Glass	Good corrosion resistance Medium Temp. Performance (90 °C) Low smoke and good flammability characteristics High impact toughness
E. I. du Pont[c]	PEKK/Graphite	High Temp. Performance (150 °C) Excellent solvent resistance High impact strength/good damage tolerance Good flammability characteristics Not sold commercially
Thermoplastic Composites[d]	PPS/Graphite PEEK/Graphite	Commingled tow Can be woven or fabricated into unidirectional tape
BASF	Commingled tow	BASF produces a variety of commingled Tows from polymers that can be spun into filaments.

[a] Technical Data Sheet, ICI-Fiberite 602-730-2000.
[b] Technical Data Sheet, Phillips Petroleum 918-661-1984.
[c] PEKK Technical Data Sheet, E. I. du Pont 800-453-8527.
[d] Technical Data Sheet, Thermoplastic Composites 704-529-8253.

Table 4. Advantages and disadvantages of various feed stocks

Feed Stock	Advantages	Disadvantages
Melt impregnated	Fully impregnated Easy to consolidate Uniform resin content viscosity	Boardy Limited by resin
Powder impregnated: consolidated	Fully impregnated Easy to consolidate	Boardy Resin must be in fine powder form
Powder impregnated: sheath/core	Flexible	Difficult to consolidate Resin must be in fine powder form
Commingled	Flexible Uniform resin content	Difficult to consolidate Limited to resins that can be spun
Solution coated	Easy to consolidate	Boardy May have residual solvents Limited by solvents for some resins
Slit tape	Fully impregnated Easy to consolidate Can be slit in variable widths	Boardy Fibers are cut along edges

a feed stock for filament winding it is important to look at matrix uniformity and distribution, fiber volume control, amount of impregnation, and the amount of fiber damage that has occurred during resin application.

1.2 Thermoplastic Filament Winding Philosophy

There are two philosophies for thermoplastic filament winding. The first is to wind and tack the tows together, and then post-consolidate the material into the final part. This method is similar to the process used to cure thermoset resin systems and will not be discussed. The second concept is to in-situ filament wind and consolidate. In this process the incoming feed material is heated, melted, and bonded to the part during winding. After winding is completed, the part is totally consolidated and may be machined to the final shape.

In-situ winding offers many advantages over other methods of winding. One of these advantages is lower residual stress in the final part. This allows thicker sections to be wound without cracks or delaminations due to internal residual stresses. Since there is no chemical reaction occurring during winding (as with thermoset resins) the winding can be stopped and started at any time without the concern of the resin curing. Also, final parts contain much lower fiber waviness then autoclaved parts since each layer is bonded to a previously consolidated layer, and the fibers do not flow during processing. The economic advantage over autoclaved parts has been shown to be 20%–40% [1] cost savings in the final part due to lower labor and capital costs. With all of this advantages and since this is a new technology area, this paper will only deal with in-situ thermoplastic filament winding.

2. State of the Art: In-situ Thermoplastic Filament Winding

In-situ thermoplastic filament winding can be broken down into three basic process parameters: tow heating, guiding, and compaction. In the ideal process, the incoming tow is molten and applied to a molten spot on the mandrel. Sufficient pressure is used to consolidate the incoming material to the existing part. In reality, each of these steps can be achieved using many different techniques. The material can be heating using

- hot gas (air or nitrogen)
- heated shoe
- infrared heaters
- lasers
- ultrasonics
- microwaves
- induction

A heated mandrel can also be used to assist in heating and consolidating the material.

Pressure can be applied to the laydown point using

- rollers
- tension
- shoes
- belts

And guiding can be accomplished by using

- D-rings
- eyes
- pins
- rollers

By combining one or several of these processing parameters, an in-situ filament winding process can be developed. The most important parameter to control during processing is temperature. If the polymer is not up to the processing temperature, it will not bond to the part. On the other hand, if the polymer is overheated, it will degrade. The following is a review of techniques used to in-situ thermoplastic filament wind.

Brandt [2] developed and patented the first thermoplastic filament winding process in 1978. In his process, an extruder was coupled with various forms of reciprocating heads to continuously fuse material around a cooled rotating mandrel to form pipe. Consolidating rollers combined with hot shoes or hot gas jets were used to achieve cohesion between the incoming strands and previously laid material. The process was applied to small diameter thin pipe. For this application, fully bonded void-free structures were not critical.

The Du Pont Company has been developing thermoplastic filament winding technology since 1982. Typical parts include control shafts, drive shafts, truss structures, and prosthetic devices. Much of the data generated is proprietary; however, Egerton and Gruber [3,4] have outlined the work on thermoplastic filament winding at Du Pont. The process for thermoplastic filament winding is described in six categories: tow supply, tow preheating, tow guiding, contact point heating, mandrel heating, and post-consolidation (optional). Several heating systems are described. A comparison of thermoset vs. thermoplastic torque tubes and crush data are presented, and it was shown that the thermoplastic composites performed equivalent to and slightly better than thermoset systems. Also, lower production costs were shown with in-situ thermoplastic filament winding due to reduced cycle time and the elimination of oven and autoclave curing steps.

Kueterman [5] and Harvey [6] have outlined the general principles which are being used by ICI Americas to develop in-situ consolidation techniques. They describe processes which utilize focused heat energy at the laydown point and a chilled consolidation roller to apply pressure. Kueterman has evaluated heat transfer sources such as lasers, hot gas convection, infrared heating, conduction, and ultrasonics. Winding tension also has been employed to supply consolidation pressure.

Stine [7] has reported on the development of a thermoplastic processing head developed by Aeronca, Inc.. Ultrasonic, infrared, laser, and hot gas heating methods were investigated for interface melting. Consolidation pressure via mechanical rollers and winding tension was evaluated. The resulting thermoplastic processing head consisted of a fiber delivery guide system, which preheats and delivers the thermoplastic precursor to the compaction point, and a high-energy hot-gas heating source capable of melting the material. A pressure compensated compaction roller was used to consolidate the material against the tool surface. The system allowed them to produce near-net, consolidated parts from PPS and APC-2 precursors with both glass and graphite fiber reinforcements. They believed that precursor quality improvements and better heating configurations would produce fully consolidated parts from their system in the near future.

McDonnell Douglas Corporation is currently developing thermoplastic filament winding processes and automated fiber placement processes using in-situ consolidation techniques [7]. Using hot gas streams (air and nitrogen) for interface melting and chilled rollers for compaction pressure in the winding of APC-2®, they have manufactured 5.75-inch OD circumferential windings with good consolidation (as indicated by C-scans) from both PPS/graphite and APC-2® at unreported speeds. Results obtained with varying angle plies have not been as successful. Inner ply voids were the major problems, with intraply voids also present to a lesser extent.

Hauber [9] has developed a single-end thermoplastic winding head to be fitted on a Robotic Winding System (ROWS) from Automated Dynamics Corporation. The "hot head" winding system uses two, side-by-side, hot gas torches to heat a small zone on both the incoming tow and the previous winding. Compaction pressure is applied via a pneumatically loaded pressure roller. The processing temperature is controlled using an infrared pyrometer aimed at the laydown point. Power to the hot gas torches is controlled based on pyrometer feedback. The system has been used to produce 5-inch diameter rings from both APC-2®/graphite and J-2®/graphite precursors. Void levels as low as 10% were achieved at tow speeds of 7.5-ft/min with APC-2®/graphite and 15-ft/min with J-2®/graphite. Scale-up to large, multiple end winding would be difficult.

Heat Transfer Technologies, Inc. has developed a hot gas delivery system and nozzle for attachment to a filament winder to provide interface melting in an in-situ winding process [10]. Hot gas, up to 1500 °F, is delivered via a flex hose to the delivery nozzle that is mounted on the winder head. The nozzle delivers two flows of hot gas; one preheats the tow, and the other heats/melts the material at the laydown points. A compaction roller or winding tension is used to supply consolidation pressure.

Brunswick Corporation has developed an in-situ winding process under contract from General Dynamics [110]. Brunswick's efforts were targeted at demonstrating filament winding capabilities for thermoplastic (PEEK) impregnated tow. They experimented with a variety of processing methods using a "breadboard" assembly consisting of a tensioning system, an ultrasonic compactor, an infrared (IR) preheating oven, and a fully circumferential IR annealing oven. Using this system they were able to produce 2.5-inch diameter hoop windings with a void level of 1% at tow speeds of 10 ft/min. When larger diameter parts with varying angles and thick sections were attempted, the system was no longer able to produce parts with reasonable void levels. Variations in PEEK tow quality were noted as a contributing factor to their unsuccessful in-situ windings. Development of better heating techniques was thought to be the major hurdle to make this type of process a success.

Beyeler et al. [12] investigated the use of laser-assisted tape consolidation. They demonstrated that fully consolidated PPS/graphite rings could be manufactured using an 80-watt carbon dioxide laser and a pressure roller. Speeds up to 16 ft/min were achieved using this process. It was noted that the process was highly sensitive to changes in the operational parameters. The biggest challenge for future application to large-scale winding was thought to be controlled, laser beam guidance.

Hawsey [13] has also investigated the use of laser consolidation with thermoplastics. Oak Ridge National Labs has developed a consolidation system using a 300-watt Nd: YAG laser and a pressure roller. They used fiber optics and beam shaping lenses to develop a uniform energy density rectangular beam (3 inch×0.25 inch) at the laydown point. The system resulted in about a 40% loss in beam energy. Maximum operating speed was said to be about 1 ft/min. Most interesting was their feedback control system for controlling temperature at the laydown point. Using an IR thermometer and a computer control algorithm, the power to the laser was adjusted to maintain constant temperature at the laydown point. Laydown on contoured surfaces was thought to be possible with the use of servo-controlled beam shaping mirrors and conformable rollers, but much development is still needed.

O'Connor and Bohannan [14] of Phillips Petroleum Co. recently filed a European patent application on an improved thermoplastic filament winding process. The patent claims that using significant improvements over the techniques patented by Brandt can be achieved. Typical process conditions and resulting parts were described. It was found that with a compaction shoe temperature of 370 to 375 °C, pressure of 15–20 psi, at typical speeds of 3 ft/min., virtually void-free 6-inch diameter hoop windings could be achieved using PPS matrix precursors.

From this review of the state of the art for thermoplastic filament winding in the open literature today some general conclusions can be drawn. Most of the work in thermoplastic filament winding is in the development stage; for example, speeds are slow compared to thermoset winding, and typically only one end is used. The cost of precursor tow is still high (typically $125/lb), and there is limited experience in fabrication of parts. Design data is just being developed, and translation of mechanical properties from flat panels to parts is just beginning to be demonstrated.

3. Limitations and Needs for Thermoplastic Filament Winding

The state of the art depicted some of the general limitations in thermoplastic filament winding. This section will look in more detail at these limitations and needs.

3.1 Manufacturing Process

The speeds reported in the literature for thermoplastic filament winding range from 10–30 ft/min as compared to thermoset filament winding, which runs at 100 ft/min and can be as high as 300 ft/min for specific applications. Also, most of the processes reported use only one end of precursor tow. This limits production rates to 1–10 lbs/hr. For thermoplastic filament winding to be successful, speeds and throughput must be increased. Presently, the limiting factor seems to be energy into the system to melt the polymer. Other secondary problems also need to be solved; for example, methods of applying pressure to the two during winding to consolidate the material without damaging it and tow splicing techniques to splice in broken or new ends of tow during winding.

3.2 Process Control

Two references have reported temperature process control. Hawsey [13] used an IR thermometer to control the power of a laser, thus controlling the polymer temperature. Haubner [9] uses an infrared pyrometer to control temperature. As discussed earlier, the polymer temperature must be carefully controlled so the polymer is not overheated (resulting in polymer degradation) or underheated (resulting in poor bonding to the part). Other parameters that need to be controlled include tension, speed and laydown pressure. These controls are typically considered for steady state operation, but they will also need to be considered for unsteady state operations such as start-up and stopping of the process.

3.3 Equipment

Filament winders exist in the industry today for thermoset filament winding. Some of the equipment manufacturers include McClean Anderson, Entec, Dura Wound, and Baer. Winding heads must be developed to hear, melt, and deliver the molten tow on to the mandrel. Computer algorithms need to be developed to control the heat input in the process to account for variations in speed and laydown rates (number of ends). This equipment also needs to be structurally sufficient to apply a consolidation force at the laydown area. As stated in section 2, heat and pressure need to be applied in the right quantities and the right place to in-situ wind thermoplastic materials. For production equipment to be successful, process control must be developed and integrated into the winding systems.

3.4 Quality Assurance

Little work has been done to insure that quality parts are being fabricated. Since thermoplastic technology is relatively new, quality programs are still based on thermoset technology, including c-scans, photomicrographs, and acoustic emissions. New inspection techniques need to be developed to take advantage of this new ability to consolidate a part layer by layer. In other words, there is an opportunity to inspect a part layer by layer and have a record of how the part was built. This is not possible in the thermoset technology, since the part must be cured as one piece.

3.5 Data Base

Since thermoplastic filament winding is in a developmental state, there is limited experience in design and analysis of parts. Also design data bases that exist are mostly for prototype parts. Thermoplastic materials have different mechanical properties and processing techniques then thermoset materials. With these new properties and winding processes, new design techniques and data bases must be developed. For example, an in-situ thermoplastic wound part has lower fiber waviness then a thermoset wound part which will make it stronger in a compression loaded application. Note that this is not only a material property, but also the process by which the part was made. As new design techniques and data bases are developed they must be integrated not only the material, but also the in-situ winding process. This integrated design process needs to be used as identified applications grow.

3.6 Complex Parts

Presently, thermoset and thermoplastic winding technology centers on axisymmetric parts. As the need for automatic part fabrication grows and the parts become more complex, there will be a need for robotic winding. Robotic winding (or fiber placement) is a process where fibers are placed onto a mandrel in any prescribed path. This means the mandrel can be complex in shape, and the fibers are placed in the load path. This technology is presently a lab curiosity and seems to be limited by process control and fiber manipulation.

4. Future

The applications available to thermoplastic filament winding will depend on how well process control and quality control are developed. If these limitations are resolved, the economics will drive thermoplastic filament winding into a primary automated manufacturing process. Opportunities will start out in performance-driven applications. These may include aerospace (satellite spars, structural tubes, pressure bottles), military (rocket motor casings, gun barrels, nose cones), and recreation (golf shafts, tennis rackets, fishing rods). As design data bases are developed, other applications should start to develop, such as oil and water pipes, aircraft (pressure bottles, cowls, nacelles), industrial (drive shafts, radio and sailboat masts, sonar domes, tanks), and critical environment parts. Also, if robotic winding limitations are overcome, this opens a new arena of complex shaped parts such as aircraft (fan blades, door frames, spars, and ribs) and industrial applications (gears, connecting rods).

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Composite Sheet Forming—Thermoplastic

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Sheet forming is an economically attractive route to producing advanced thermoplastic composite parts. Most of the currently used processing techniques have been derived from the sheet-metal forming industry. Various development programs are underway in the aerospace and military aircraft industry to determine the value of this technology for composites. Some of these programs are reviewed along with current processing practices to establish the limitations of the state of the art. Critical areas of the technology for which technical advancement will have major impact on the development of this technology are presented.

Key words: autoclave forming; consolidation; continuous fiber; diaphragm forming; discontinuous fiber; preforming; press forming; sheet forming; thermoplastic composites; woven fabrics.

1. Introduction

Some of the most important potential advantages offered by advanced thermoplastic composites over thermosets are process automation and lower cost to convert intermediate material forms into end-use parts. The belief is that advantage can be taken of the processability of the thermoplastic component both to eliminate the long and expensive thermoset autoclave curing step and to offer a system where reprocessing is feasible. The term *advanced thermoplastic composite* as used in this paper refers to highly loaded reinforced thermoplastics (generally over 50% fiber volume fraction) which, because of their use in applications requiring high specific strength and modulus, are made up of layers of aligned continuous or long discontinuous fibers with specified orientations. The reinforcing fibers may be carbon, Kevlar®, or glass.

One of the most attractive processing techniques for converting thermoplastic composites to parts is sheet stamping. Cold sheet stamping is a widely used, low-cost and fast-rate process in the sheet-metal forming industry. It has been applied in various forms to unreinforced plastics, usually in high-temperature processes. Examples of this are vacuum forming, solid-phase high-pressure forming, and hot stamping, such as used in the processing of random glass fibers in polypropylene [1].

Various attempts have been made to apply these metal forming techniques to advanced thermoplastic composite forming, and the potential advantages for reduced part production costs have been documented by several authors [2–5]. These advantages come from the high efficiency of the forming process in converting sheet to a three-dimensional part and from the relatively short processing cycle required for thermoplastics compared to thermosets. Furthermore, if processing can be done in existing metal forming equipment with minimal modifications, these composites will find acceptance more easily as replacements for sheet metal. A look at the type of thermoplastic composite sheet samples being shown at composite trade shows indicates widespread interest in this area including major development efforts by suppliers and manufacturers to make this technology commercially viable.

In a typical thermoforming process, the sheet stock, or preform, is heated in an external oven or in a forming system (see fig. 1). At the forming temperature, the sheet is transferred into dies in the forming system where it is shaped to conform to the die geometry. After forming, the sheet is cooled under pressure to below the resin glass transition temperature (T_g) before removal from the forming system. Depending on the preform used, the part generally has to be trimmed to yield the final net shape. Material waste considerations are, therefore, important in preform design and the deformation path during forming.

Although the forming techniques being used for advanced thermoplastics are similar to those used for sheet metal and unreinforced thermoplastics, there are some important differences between these materials that result in differences in how they are actually applied. Tables 1 and 2 list some of these differences. In general, these imply that

- Forming of advanced thermoplastic composites is done at much higher temperature and pressure than thermoset and unreinforced thermoplastics.

- Due to the high viscosities, flow processes take longer in thermoplastic composites, and the heating and cooling times are greater because of higher temperatures.

- Maintenance or control of fiber placement and orientation during forming, required in thermoplastic composites to retain high properties, makes the deformation path more critical than in the isotropic unreinforced thermoplastic and sheet metal cases.

- Maintenance of consolidation pressure (preferably uniform) is required on the whole surface of a formed part until it cools to below the resin T_g to prevent deconsolidation. This is not a requirement in sheet metal forming and not that critical in unreinforced thermoplastic sheet forming.

The conclusion from these differences is that although the forming techniques used are similar, more sophisticated solutions need to be developed for successful processing of thermoplastic composites.

Table 1. Thermoset versus thermoplastic processing

Thermosets	Thermoplastics
Low viscosity 10–100 poise	High viscosity 1000 poise
Low temperatures 120–200 °C	High temperatures 300–400 °C
Low pressures Vacuum—150 psi	High pressures 100–2500 psi
Long curing times	Fast heating and cooling rates*
Autoclave capital investment	Autoclave not required*
Refrigeration	No refrigeration
“Wet” process	“Dry” process

*Biggest processing advantages

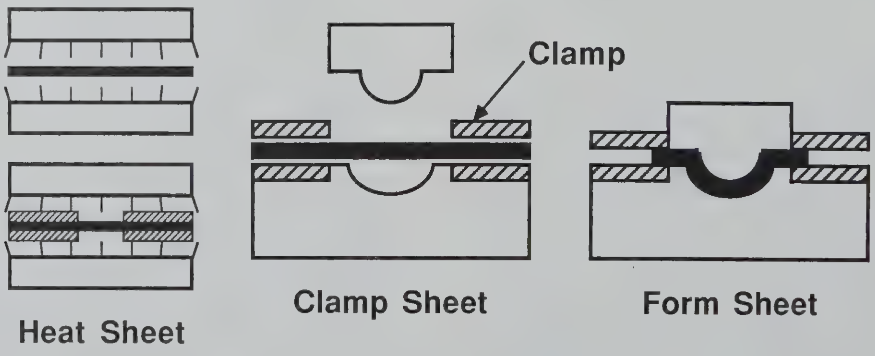

Figure 1. Schematic of typical press forming process using matched dies.

Table 2. Typical forming characteristics

	Unreinforced thermoplastics	Sheet metal	Advanced thermoplastic composites
Sheet heating	IR, convection	None	IR, convection
Sheet characteristic at process temperature	Pliable, drawable	Drawable	Drawable in discontinuous fiber systems only
Sheet structure	Isotropic	Isotropic	Anisotropic
Composition	Homogeneous	Homogeneous	Heterogeneous (Two-component)
Process temperature	Medium T_g+50 to 75 °C	Low Room	High 280 to 390 °C
Cycle time (Minutes)	Short (Minutes)	Very short (Fractions)	Long (Tens of Minutes)
Deformation loads	Low	Medium to High	Medium to High
Consolidation pressure	Low (Vacuum)	None	High 100 to 1000+psi
Mold temperature	Low (Below T_g)	Room	High (Sheet Temp.)
Compensation for thickness variations in matched-dies	Yes	Yes	Not Easily

2. Review of State of the Art

The literature on advanced thermoplastic forming is not extensive because the technology is new. However, the breadth or scope of recent reported work in this area is rapidly expanding. The earlier work dealt with the use of existing sheet-metal forming equipment and technology to demonstrate the potential for shaping continuous fiber composites [3–5]. Subsequent papers looked at deformation mechanics but were limited to woven fabrics and purely kinematic analyses of formed hemispheres that ignored true deformation behaviors of these composites [6–8]. These first-level approximations have provided needed insight into forming mechanics and laid the foundations for more complex analyses. Material flow behaviors have now been incorporated in recent work to predict the geometry and fiber structure of some simple shapes [9–11]. Ultimately, these analyses have to enable the prediction of properties or performance of formed parts. This ability seems a little further away, but properties of formed parts and their dependence on forming parameters are now being reported [10,12,13]. A systematic approach that involves the generation of material constitutive equations is beginning to emerge [15–17]. Finally, as the understanding of the material requirements for forming grows, novel approaches to overcome limitations in current material forms or forming methods are being introduced [2,18].

2.1 Available Material Forms

One of the most important decisions to be made in developing a system for producing a part is the choice of a sheet structure to use. At this time, the main concern is availability, since most sheet materials are offered only in developmental quantities by manufacturers. The general classifications are woven fabrics, unidirectional fiber tapes (referred to in this paper as uni-ply), and random-fiber sheets. When the first two are plied together in multi-angle, multi-ply configurations, the resulting sheets are referred to as *multi-ply laminates*. Random-fiber sheets will not be discussed here, since they are not generally considered advanced composites as defined earlier. Comments will be limited to structural applications where controlled ply lay-up and fiber orientations are required.

Table 3 lists the different material forms that have thus far been introduced in the market for sheet forming. Besides the resin properties, which determine processing temperature, viscosity, and thermal properties, the fiber structure in the sheets represents major distinctive features from a processing standpoint. Hence, for forming analyses, these materials are broadly categorized as continuous or discontinuous, unidirectional tape or woven fabric, and consolidated or unconsolidated (commingled fibers or powder-impregnated) forms. No single resin will be stressed, since for a given fiber structure, changing the resin does not significantly change the forming behavior except the magni-

Table 3. Commonly referenced advanced thermoplastic composite forms

Trade name	Supplier	Resin	Resin type	Fibers	Fiber form	Sheet structure	$T_g/T_m/T_{proc.}$ °C	Comments
APC-2	ICI	PEEK	Semi-crystalline	Carbon glass	Continuous	Uni-tape	144/340/380	
HTX	ICI	PAK	Semi-crystalline	Carbon glass	Continuous	Uni-tape	205/386/420	
LDF™	Du Pont	PEKK	Semi-crystalline	Carbon glass Kelvar®	Discontinuous	Multi-ply sheets, Woven ribbon tow fabric	156/338/370	
Ryton®	Phillips Petroleum	PPS	Semi-crystalline	Carbon glass	Continuous	Uni-tape, woven fabric & ribbon tows	85/285/343	
—	Quadrax	Various	Semi-crystalline	Carbon glass Kelvar®	Continuous	Woven ribbon tows	—	
—	BASF	PEEK PPS,PEI	—	Carbon glass	Continuous	Powder Impregnated, Commingled fibers Uni- & woven fabrics	—	Unconsolidated Tacky
Filmix®	Heltra/ Courtaulds	PEEK	Semi-crystalline	Carbon glass	Discontinuous	Commingled/ co-spun twisted yarn uni-tape & woven fabric	144/340/380	Unconsolidated
CYPAC®	American Cyanamid	PEI	Amorphous	Carbon glass	Continuous	Uni-tape Woven fabric	217/—/343	
RAYDEL®C	Amoco	PAE	Amorphous	Carbon	Continuous	Uni-tape Woven fabric	260/—/350	
RAYDEL-X	Amoco	PAE	Amorphous	Carbon	Continuous Woven fabric	Uni-tape	220/—/350	
PAS-2	Phillips Petroleum	PAS	Amorphous	Carbon glass	Continuous	Uni-tape	215/—/330	
HTA	ICI	PES	Amorphous	Carbon glass	Continuous	Uni-tape	260/—/330	

tudes of the forming parameters such as temperature and pressure. Besides the differences in properties, such as solvent resistance, amorphous resins are generally more forgiving in terms of having a broader processing temperature window, and they do not have problems with the dependence of the rate and degree of crystallinity on temperature history as do semi-crystalline resins.

The choice of either fabric or uni-ply laminates depends on the part's geometrical and mechanical specifications. Traditional woven-fiber structures based on tows with rounded cross-sections generally have lower strengths than uni-ply laminates at the same fiber volume fraction (FVF). However, in cases where such stringent fiber property translation is not required, and especially in quasi-isotropic lay-ups, the preference in the past has been to use fabrics because of the ease of handling. This is especially true for thermoset pre-pregs. For thermoplastics, handling is an issue at high temperature when a heated sheet has to be transferred into dies for forming. Another major consideration, however, is fiber interactions and displacements during forming. Fabrics tend to prevent gross fiber motions which could be both a blessing and a curse. It is a blessing in that this helps to restrict lateral fiber displacements and aids uniformity in fiber orientation and distribution. On the other hand, these restrictions in motion can result in fiber wrinkling where intra-ply fiber slippage is required to accommodate large localized motions in complex moldings.

Some of the more innovative material forms that have been introduced to overcome limitations in sheet structures based on pre-impregnated and consolidated straight uni-ply and woven continuous fibers are the discontinuous fiber system from Du Pont's LDF® technology, the weaving of thermoplastic impregnated tows with tape or ribbon-like cross-sections, and powder-impregnated or commingled continuous fibers (see table 3).

The LDF® formable sheets consist of aligned discontinuous fibers in a thermoplastic matrix. The fibers are typically Kevlar®, carbon, or glass with average fiber length in the 1- to 6-inch range and a degree of alignment similar to that of continuous fiber tape. The most important characteristic of the LDF® formable sheet is its drawability. Drawing is achieved by the sliding of the discontinuous fibers past one another. If the deformation is uniform, extensive axial draw is achievable, and continuous fiber-like properties are maintained.

The availability of consolidated thermoplastic composites in the form of ribbon-like tows or mini-tapes (slit from wide tapes or otherwise) has resulted in woven forms in which there are no twists. These woven forms enable better translation of fiber properties in laminates (close to or equal to 0/90° uni-tapes) than has previously been possible with standard woven fabrics.

When thermoplastic composites were first introduced, the tendency was to manually lay them up like thermoset prepregs. However, the tapes were stiff and boardy and did not lend themselves easily to standard thermoset techniques. Unconsolidated powder-impregnated and commingled fiber forms were introduced to overcome these difficulties and provide drape and tackiness. BASF is currently the main supplier of these composite forms, which tend to require longer cycle times because both the resin impregnation and consolidation are done during the part forming process.

Another sheet form recently reported on is one based on the excess filament length concept where excess fiber length is built in during lay-up of continuous fibers [18]. The excess fiber length is pulled out during part forming and provides drawable features similar to the aligned discontinuous fiber structure.

2.2 Sheet Preforming Techniques

One of the steps in sheet preparation, known as pre-forming, involves the laying up or cutting of sheet into a particular shape or structure. Preforming is an important step in that the initial geometric state or shape and level of consolidation of the preform influences the subsequent deformation path during forming and ultimately the shape and quality of a formed part. The property requirements in the formed part dictate the ply lay-up such as unidirectional, quasi-isotropic or others. In general, the same lay-up configuration called for in the final part has been used in the workpiece before forming on the expectation that it is preserved during the deformation process. In addition, the use of a flat sheet of uniform thickness and ply orientations is desirable because it eliminates the extra cost of customization or sheet tailoring. However, since the deformation process is material dependent and is not currently that well understood to enable control of ultimate fiber movement, one cannot arbitrarily place fibers in the initial sheet and expect them to end up where desired. In a large class of structural parts where fiber placement is important, sheet tailoring becomes very critical. To do this successfully, one has to understand the deformation behavior of the sheet in the forming process being used. The deformation behavior (see Deformation Analysis: Mechanics, sec. 2.6) relates the initial fiber configuration to the final one after deformation. This knowledge enables one to preform a sheet to achieve uniform deformation, optimum fiber placement (to maximize properties), and reduced material waste. A simple example of sheet tailoring is the use of excess ply build-up in locations that thin out more than the rest of the workpiece during deformation [19]. Another commonly used technique, especially with continuous fiber fabrics, is the placement of slits and ply overlaps in areas that would normally require considerable draw. The level of consolidation also influences the sheet deformation behavior. For example, it is known that in diaphragm forming of continuous carbon fiber/PEEK composites, using a loose ply stack of pre-consolidated single uni-ply layers gives better conformability than a pre-consolidated, thick multi-ply sheet because the individual layers can act independently (due to less inter-layer interaction) and prevent fiber buckling or wrinkling [12].

2.3 Forming Techniques

The forming method used, in general, determines the cost to produce and the quality of the part. The choice of a particular method depends on the level of capital investment desired and the effect of the method's deformation path on the fiber distribution in the resultant part. A discussion of the cost of forming systems is outside the scope of this paper. Table 4 gives an overall comparison of the major processing methods currently being used in forming. These are matched-die press forming, diaphragm forming, hydroforming, autoclave forming, vacuum forming, and rubber pad press forming. Discussions of these methods follow.

2.3.1 Matched-Die Press Forming Matched-die press forming is the most common and probably the most widely used forming system. This is because forming presses are readily available from very simple, hand-operated small presses to fairly sophisticated computer-controlled hydraulic systems. For simple forming operations, standard heated platen presses that have generally been used for flat panel molding have proven to be adequate. However, in operations where the control of deformation rate and pressure history are important, high quality stamping presses are used.

The dies used in this forming method are generally made of metal, which can be internally heated and/or cooled. When metals are used, the dies are generally designed to fixed gap (thickness) of close tolerance. High pressures can easily be applied to the workpiece. A disadvantage of this forming method is that when there is a thickness mismatch between the formed piece and the pre-machined cavity, non-uniform pressure is produced on the

Table 4. Sheet forming methods and equipment

	Advantages	Disadvantages
Vacuum forming	Low pressure	Low force, impractical
Matched metal die press	Close tolerance High forming load and pressure	Thickness mismatch Friction at die interface Non-uniform deformation/pressure Long heating/cooling times High fabrication cost
Hydroforming	Only one solid die, undercuts high pressure	Low temp, no peripheral equipment
Diaphragm forming	Good fiber placement control	Long cycle time Temperature limitations
Rubber pad forming	Only one solid die High pressures	Lack of complex details Temperature limitations

part resulting in non-uniform consolidation (see Part Consolidation, sec. 2.5.4). It is also difficult to control fiber displacements because the non-deforming fixed geometry of the dies permits only point or localized, rather than uniform, loading of the entire surface of the workpiece. This limits localized control of the deformation path of the workpiece. Where heating and cooling are desired, the dies usually have such a high heat content that heat transfer times are long. Finally, matched-die fabrication costs are high because of the requirement that the two close-tolerance die halves have to match. Substituting an elastomeric material in place of one of the die halves usually reduces the cost and enables the application of a more uniform consolidation pressure than in an all-metal die set.

2.3.2 Diaphragm Forming In diaphragm forming, the workpiece is held between two disposable plastically deformable diaphragms. The diaphragms are then clamped, heated with the workpiece to the processing temperature and deformed over a tool half using a combination of air pressure and movement of tool in contact with the workpiece, which is usually under vacuum throughout the process (see fig. 2). In continuous fiber composite forming, the workpiece is not clamped and is allowed to slide within the diaphragms. This sliding action creates tensile stresses in the sheet from interfacial shear stresses that reduce wrinkling. When the workpiece is a drawable (extensible) sheet such as an LDF® formable sheet, it can be clamped along with the diaphragm, and the sheet deformation is then very similar to that of the diaphragms. Forming of more complex shapes is, therefore, possible in this case. Figure 3 shows an example of a part formed using an LDF® Kevlar® aramid/J-2 polymer composite in a superplastic aluminum diaphragm forming system where the sheet draws in a way similar to that of the diaphragm.

Since the workpiece is under compression normal to the surface and the actual deformation rate is slow (controlled by the creeping of the diaphragms), control of lateral fiber motions for simple part geometries is usually good. The geometric complexity of parts made, however, is limited by the deformation of the diaphragm, and since the diaphragm material deforms in a finite temperature range, only materials that can withstand these temperatures can be used. Currently, the diaphragm materials in use are superplastic aluminum and polyimide films (Du Pont's Kapton® and UBE Industries' Upilex-R®). Typical diaphragm forming temperatures are 400 °C for superplastic aluminum and 300 to 400 °C for the polyimides. In addition, cycle times for current forming systems are long (of the order of 90 to 120 minutes) due to heating and air cooling of the massive pressure chambers used to provide the pneumatic forming pressures. With the use of specially designed low thermal inertia tooling and chamber pre-heating, 60-minute cycle times have been achieved [12,13]. Further, attainable maximum forming pressures may be severely limited due to knock-down factors associated with operating these pressure chambers at the high forming temperatures required for thermoplastics.

2.3.3 Hydroforming Hydroforming is similar to diaphragm forming in that a fluid medium, usually a hydraulic fluid, behind a rubber diaphragm, is used to deform the workpiece against a male or female tool half (see fig. 4). The main difference is that the rubber diaphragms in hydroforming are a permanent part of the forming system and are usu-

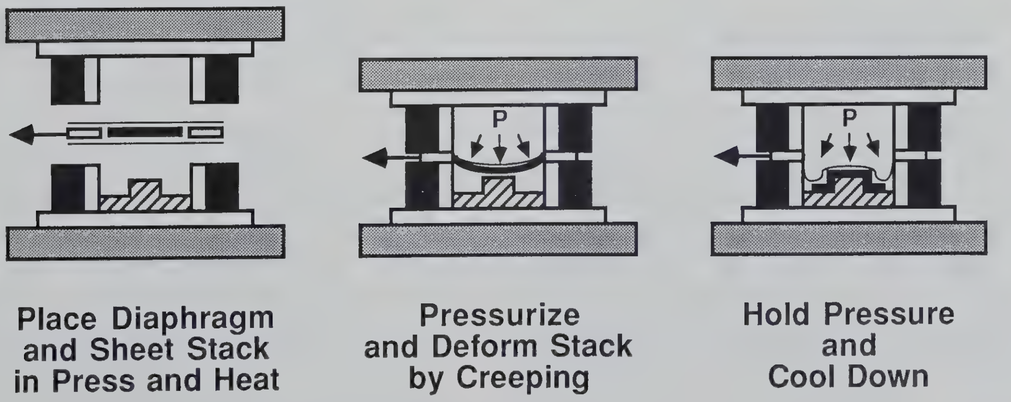
P
P
Place Diaphragm and Sheet Stack in Press and Heat
Pressurize and Deform Stack by Creeping
Hold Pressure and Cool Down

Figure 2. Diaphragm forming schematic (courtesy of University of Delaware [9]).

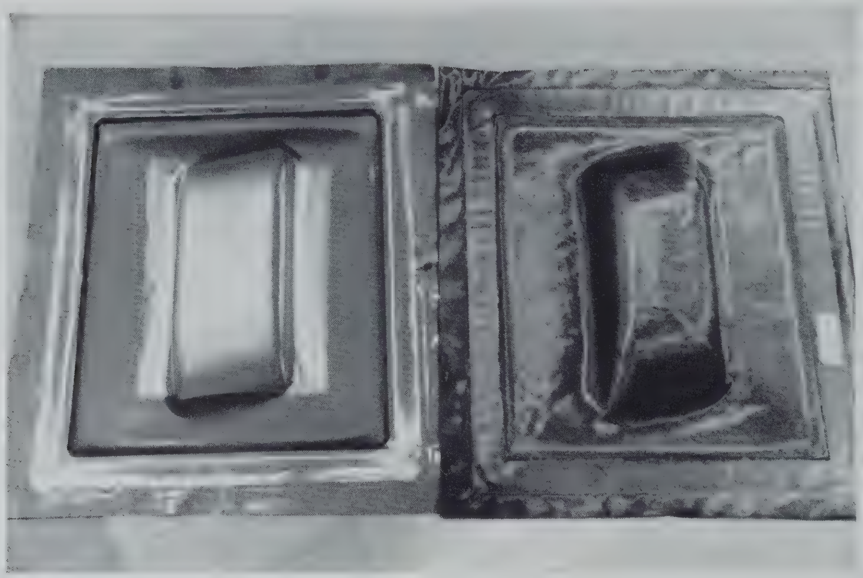

Figure 3. Photograph of ordered staple rectangular formed piece using diaphragm (superplastic aluminum) forming (left, diaphragm; right, composite).

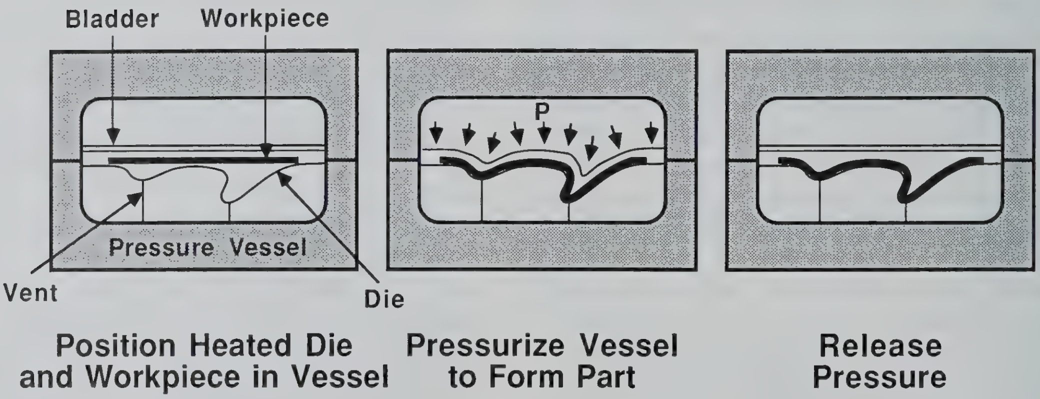
Bladder
Workpiece
Pressure Vessel
Vent
Die
P
Position Heated Die and Workpiece in Vessel
Pressurize Vessel to Form Part
Release Pressure

Figure 4. Hydroforming schematic (courtesy of ASEA Metallurgy).

ally much larger than the workpiece, and only one is used. However, since the rubbers used in these systems are suitable only for lower temperatures, extra disposable rubber sheets are placed over the workpiece before forming to prevent diaphragm rupture due to high temperatures or sharp points on tools. Hydroforming systems have been in use extensively in the sheet-metal forming industry. They are usually massive systems capable of up to 10,000 psi pressure. The high pressures allow undercuts to be formed. However, the use of the additional rubber sheets that can be as thick as one-half to one inch can limit how small cavities can be and still obtain good tool definition. The tooling can be heated using the tool bed that is moved into the forming area. Because the whole system is pressurized, it is impractical to use peripheral equipment or devices such as clamps and cooling and heating lines connected to the tool itself.

2.3.4 Autoclave/Vacuum Forming Autoclaves, which have traditionally been used for thermoset composite curing, are now being increasingly used for thermoplastics. This is because they provide a natural extension for thermoset molders interested in developing thermoplastic processing know-how by using equipment that is already installed. The principles of autoclave processing of thermoplastic composites are not that different from hydroforming or diaphragm forming. The cavity between the workpiece and the tool is generally evacuated or exposed to atmospheric pressure to create the pressure differential necessary to deform and consolidate the workpiece (see fig. 5). If the pressure in the autoclave is atmospheric and the evacuated cavity is under vacuum, the process is essentially just vacuum forming. For thermoplastic composite forming, vacuum forming is impractical because higher pressures are generally needed for deformation and consolidation in reasonable time scales. Just as in diaphragm forming, cycle times for processing are long due to the large thermal inertia in heating and cooling the whole system. However, with clever die-design, it is possible to heat only the tooling or the pressurizing air resulting in short cycle times. The need for only one tool half reduces tooling cost for autoclave processing.

2.3.5 Rubber-Pad Press Forming In rubber-pad forming, one tool half is replaced by a thick pad of rubber that conforms to the solid tool half under pressure in a forming press (see fig. 6). The rubber pad can be profiled to the tool geometry but is permanently attached to the press platen and is generally much larger than the tool. This contrasts with rubber matched-die tooling, where the rubber is matched to the metal tool half. This process provides high forming pressures that are not uniform over the workpiece. The pressures are determined by the local extent of deformation and approach uniformity for parts of very shallow draw. This limits the complexity of parts that can be formed with good die detail. To obtain a good level of draw, the bulk of the rubber pad is made of a more compliant foam material such as polyurethane with

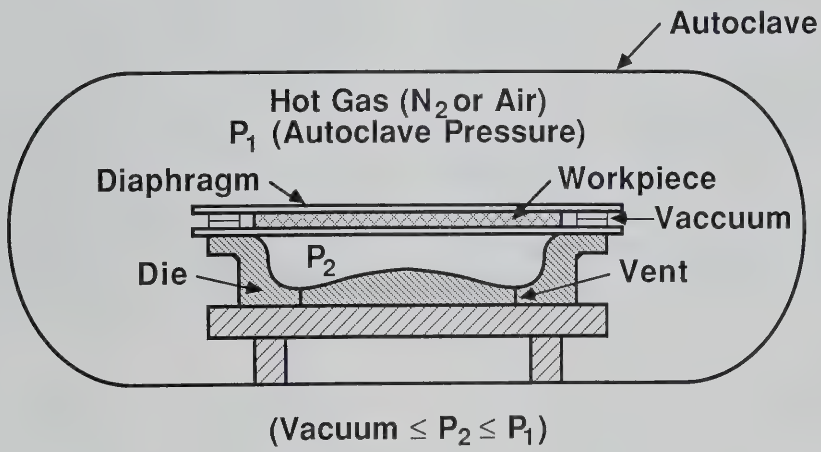

Figure 5. Autoclave/vacuum forming schematic.

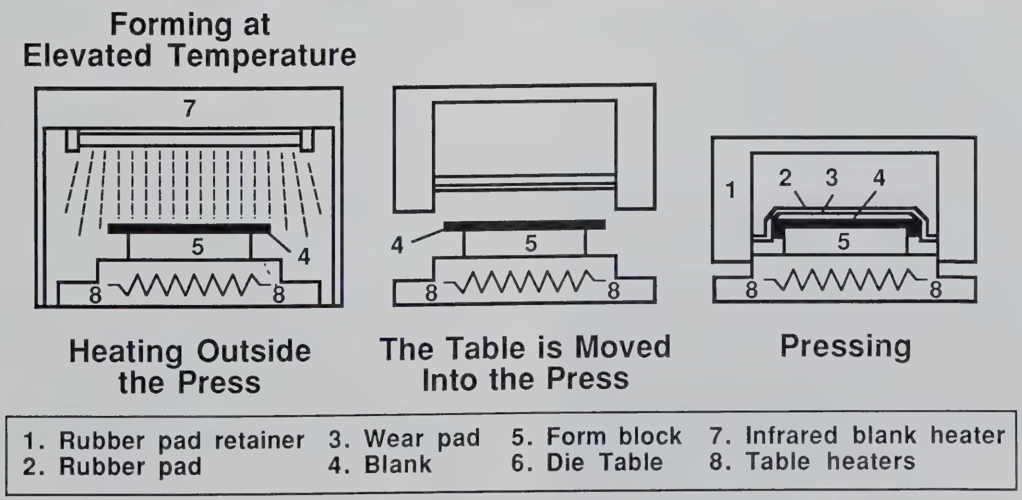

Figure 6. Rubber pad forming schematic (courtesy of ASEA Metallurgy).

a cover pad of silicone rubber to enable high-temperature forming. The use of foam, thus, imposes temperature limitations in using this technique. In addition, current silicone rubber materials may be limited to 230 to 290 °C in air.

2.4 Forming Tools

The design of forming tools and the choice of tool materials are an integral part of the forming process specification. However, more often than not, tooling does not usually get the attention it deserves during process specification. On the other hand, forming dies ultimately determine the geometric accuracy of formed parts and, in cases where the production lot is small, a significant portion of the part fabrication cost. Design issues are similar to those for sheet-metal dies or molds for unreinforced plastics, except that there may be a need to pay special attention to differences in coefficient of thermal expansion. Due to the high temperatures and pressures required to process advanced thermoplastic composites, the choice in material selection is very limited. In general, dies are made from steel, aluminum, metallic alloys such as Kirksite (castable) and Invar, or castable or chemically bondable ceramics such as ComTek®. All these materials have limitations when applied to thermoplastic composite sheet forming (see table 5). It is not known if any of the high-temperature composite tooling materials used for thermosetting composites have yet been applied to thermoplastic forming. Even though these should be applicable in autoclave type processing, it is not clear if such tooling materials will withstand the impact and concentrated loading that are characteristic of press forming operations. Tooling requirements differ for the various forming techniques as has been discussed in Forming Techniques, section 2.3. For example, for autoclave type forming, it is possible to use thin-shelled dies to reduce thermal inertia because of the inherent hydrostatic loading conditions [12,13]. However, such dies would not be suitable for press type forming situations because they would not be structurally adequate. Also, undercut and vertical wall consolidations are easily incorporated in diaphragm and autoclave forming tools but are not easy to implement in matched-die press forming tools. By far, the most significant factor to be considered currently in tool design is cost. Since no parts are currently in full-scale production, there is a need for low-cost tools for development programs that do not compromise quality or requirements to allow a true assessment of this technology. Most of the tools that have been fabricated for these development programs are

Table 5. Tooling materials and limitations

Tool material	Type	Fabrication method	Cost range	Max. temp. °F	Dimensional stability	Resistance to impact	CTE in/in °F (10^{-6})
Aluminum alloy	Metal	Machine or cast	Medium	600	Fair	Fair	
Steel	Metal	Machine	Medium High	1000	Good	Good	
Invar	Carbon, nickel, steel alloy		Medium High				1.5–6.0
Kirksite	Zinc alloy	Cast	Medium	715	Good		
Comtek™ (OxyChem)	Ceramic	Chemically bonded		800			4.0
CeraCom (C/SiO_2) (ComTool Tech)	Carbon/ Ceramic	Heat curable @350 °F (Pre-preg)		2000			0.225
Silicone rubber	Elastomer	Cast		600	Poor	Fair	
Polyimide	Carbon composite	Hand lay-up		750			
Epoxy	Carbon	Cast or hand lay-up		250–350			2.5

essentially production tools because no materials exist that meet the stringent temperature and pressure requirements for the processing techniques while still being inexpensive and easy to fabricate.

2.5 Processing Steps

The key processing steps required for forming parts involve heating the sheet to be formed, placing it inside dies, shaping it by forming, and cooling it under pressure to consolidate it. These steps are now discussed separately in a bit more detail in the following sections.

2.5.1 Sheet Preparation/Heating Typical sheet preform heating methods include infrared (IR) radiation, conduction (e.g., heating between two heated platens or plates), and convection (in air or inert gas circulation oven). Each method of heating has its advantages and disadvantages. For IR heating, heating time is usually short (of the order of a minute or two), but for thick sheets, temperature gradients develop through the thickness. Depending on sheet thickness, conduction heating can be configured to provide heating times similar to IR, but heated sheets tend to stick to the contact surfaces, making handling difficult. Convection heating usually takes the longest (of the order of 5 to 10 minutes or more depending on sheet thickness), and the use of inert gas is preferable, just as in IR heating, to prevent oxidation of the polymer at high temperatures.

2.5.2 Transfer to Dies Sheets to be formed are usually heated to the melt temperature of the resin. At this temperature, the sheets are very flexible, deconsolidated (if not heated under pressure), and easily distorted. This makes handling very difficult, especially for large thin sheets, if they are heated outside the forming system and have to be transferred. In this case, some form of framing is required to hold the sheet for transfer into the forming die. Transfer times are of the order of a few seconds to prevent significant cooling. The use of high closing press speeds further reduces the total length of time the heated sheet is exposed to lower temperature environments before tool contact and deformation takes place. When the forming system permits, heating inside the dies without sheet transfer is desirable for isothermal forming. However, this does not allow forming with dies at a lower temperature than the sheet. Heating in a vacuum bag during diaphragm forming provides the best means of reducing resin degradation due to oxidation.

2.5.3 Sheet Forming/Fiber Placement The deformation step in a forming process is just a means to redistribute the fiber and resin in a composite over a 3-D curved surface. Success in using this to make an acceptable part is based on placing the fibers and resins at desired locations to attain required properties. The control of placement of fibers is one of the most important criteria in the selection of a forming system. In general, for continuous fibers, lateral fiber displacements must occur to accommodate the increasing or decreasing surface area associated with going from a flat surface (sheet) to a curved 3-D surface. The best control of placement is achieved when individual fiber filaments, tows, or tapes are laid down manually, with tape laydown equipment, or by filament winding over the surface of a mold or mandrel. These are usually slow processes and not as cost effective for the shapes of interest compared to sheet forming. However, in sheet forming, control is limited because only portions of the sheet can be loaded at a time and the rest of the sheet is displaced according to the material deformation behavior. The forming system that tends to give better fiber placement control for multi-ply continuous fiber composites in simple geometries is diaphragm forming because forming stresses are generally applied over the whole surface of the sheet. However, even in this case, consolidation pressures and inadequate shear stresses on the sheet surface can give rise to unwanted fiber placement leading to tow splitting and transverse flow (see fig. 7). These effects have been treated in detail in references [9,10,20].

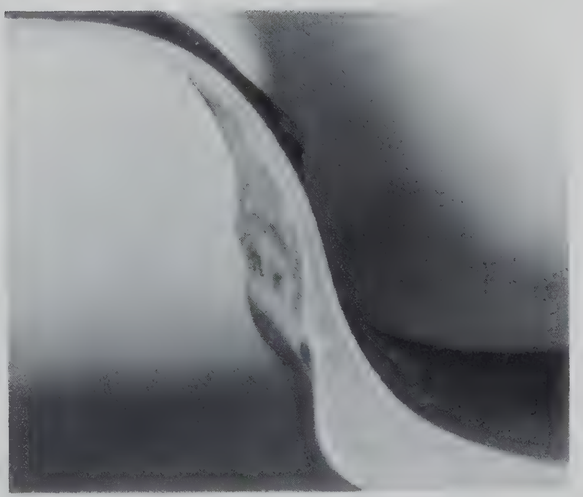

Figure 7. Photograph of a cross section of a formed disk part showing lateral fiber displacement (courtesy University of Delaware [9]).

One result of undesirable fiber placement is fiber wrinkling. This occurs when the fibers are loaded in compression during deformation resulting in fiber buckling. An example of how this occurs is shown in figure 8 for the formation of a hemispheric shape from a flat sheet consisting of multiply layers of continuous fiber. A point, X, on a radial fiber in the initial sheet moves a distance, d, to point Y due to fiber pull-in. As a result of interply shear, adjacent plies are pulled in the same distance or less depending on the level of shear stresses. (A woven fabric will tend to have the most severe case; hence, in the ideal situation, cross fibers will move in the same amount as the radial fibers.) In the worst case of 90° plies, a radial displacement, d, results in circumferential decrease of d per radian, which has to be accommodated by one or a combination of the three modes of fiber deformation. Two of these modes are the much less desirable in-plane and out-of-plane buckling. A preferred mode is in-plane curvature, which occurs when other stresses, such as one induced on surface plies through normal loading in diaphragm forming, counteract the inter-ply drag due to the pull-in of the radial fibers. A drawable material, such as the LDF® material, reduces or eliminates the fiber pull-in distance, d, and hence reduces or eliminates the excess fiber length that can cause buckling or in-plane curvature in the cross fibers. In a sheet where both inter-and intra-ply slip occur (i.e., the fiber filaments act independently), it may be possible to perform the deformation in such a way that the sheet is in tension all through the deformation process; hence, no buckling will occur. Figure 1 is one scheme for clamping a sheet during forming to produce tensile stresses. By controlling the normal pressure the sliding sheet produces the desired shear stresses due to friction which translates into tensile stresses in the sheet. The ultimate control is obtained when the tension in smaller segments of the sheet can be controlled independently. When there are fiber interactions, such as in a woven fabric, the permissible deformation required by the geometry of the part being formed makes it difficult, in most cases, to form 3-D shapes without wrinkles. For example, in forming a hemisphere, the only way wrinkling can be prevented or minimized is by allowing very severe rotations in the fibers and using extremely fine weave (see fig. 9). Therefore, fiber bundle locations cannot be independently specified. An LDF® formable sheet minimizes this wrinkling phenomenon by stretching the material in tension to accommodate the increased area rather than pulling in fibers, which tends to induce compressive stresses due to fiber interaction as discussed earlier.

2.5.4 Part Consolidation Besides the local fiber volume fraction (FVF) and orientation, the level of consolidation determines the level of mechanical properties attainable in a composite. A poorly consolidated composite has voids that reduce the load-carrying efficiency of the reinforcing fibers. Consolidation in a thermoplastic composite is achieved by applying pressure for a certain length of time at the melt temperature of the resin. Depending on the initial state of the composite (whether or not it is pre-impregnated) the pressure and time vary from vacuum to 600 psi and 1 to 20 minutes or more, respectively. In general, when a thermoplastic composite is heated to the melt, the

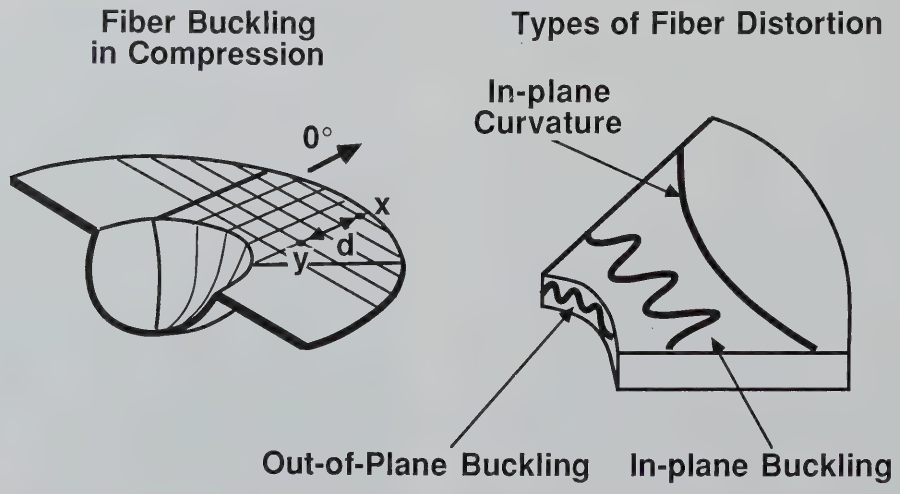

Figure 8. Cause of fiber wrinkling during forming.

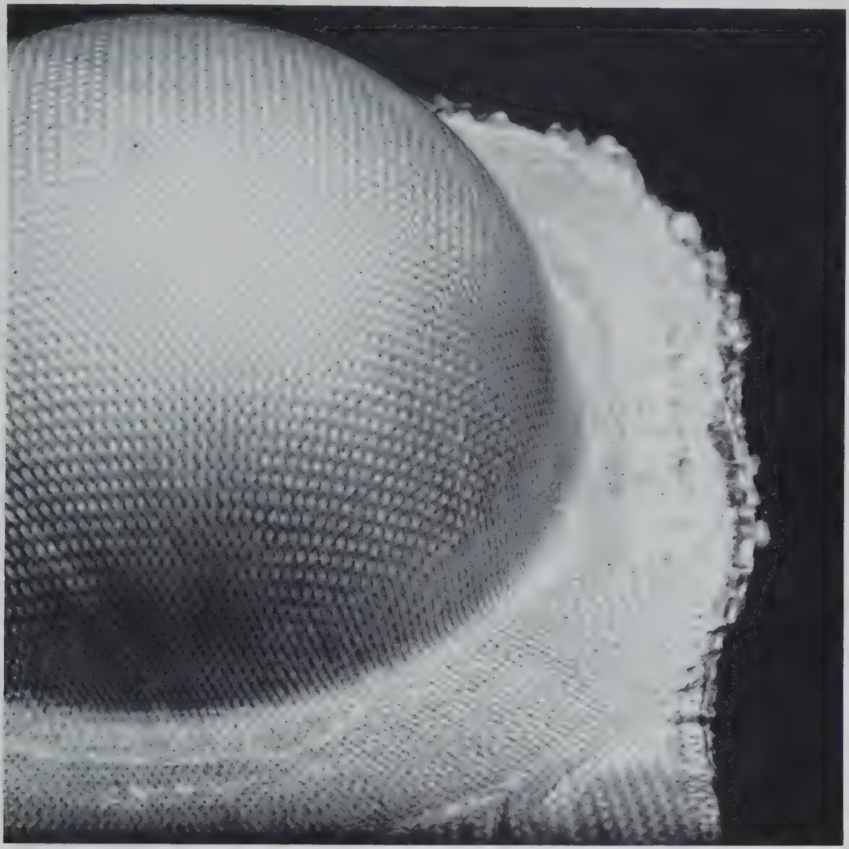

Figure 9. Formed hemisphere of continuous fiber fabric.

sheet deconsolidates unless heated under pressure. After such a sheet is deformed, a re-consolidation step is required to achieve ultimate mechanical properties. Diaphragm forming is different in this respect because the sheet is heated and formed under at least vacuum pressure, so deconsolidation in general is minimized. In matched-die and rubber-pad forming, the sheet may be heated outside of the forming dies and usually under no pressure, so the formed sheet deconsolidates. Applying a non-uniform consolidating pressure may result in resin squeeze-out, squeeze flow, and non-uniform consolidation. The nature in which this pressure is applied is, therefore, important. Autoclave and diaphragm forming systems inherently provide uniform pressure, although in practice die design or incompletely deformed diaphragms may produce non-uniform consolidation pressure [9]. Non-uniform consolidation pressure is especially a problem in matched-die tooling, where thickness distribution in formed parts produces high spots that become highly pressurized areas whereas low spots are subjected to near zero pressure. Consolidation is why knowing thickness distributions and matching die cavities to them is important in matched-die tooling. Also, the high stiffness of metal dies means that surfaces oriented at an angle other than perpendicular to the loading direction have pressures reduced by the cosine of the out-of-plane angle. Hence in forming a hemisphere, the surface is not pressurized uniformly. Special techniques are therefore required for consolidating vertical surfaces or undercuts. Furthermore, a die with surfaces at various angles to the principal loading direction and designed for a particular gap and sheet thickness will not be suitable for consolidating a sheet of a slightly different thickness. As an example, if the sheet thickness, T, in figure 10 changes by ΔT, the bottom die gap changes by $\Delta T/\cos\Theta$, which is larger than ΔT. Hence, a rigid solid tool will not contact the sheet in the bottom! The use of a flexible tool half to provide some sort of hydrostatic pressure is therefore more desirable. Elastomeric materials, such as silicone rubber, have been used extensively as such consolidation media but have limited high-temperature usage.

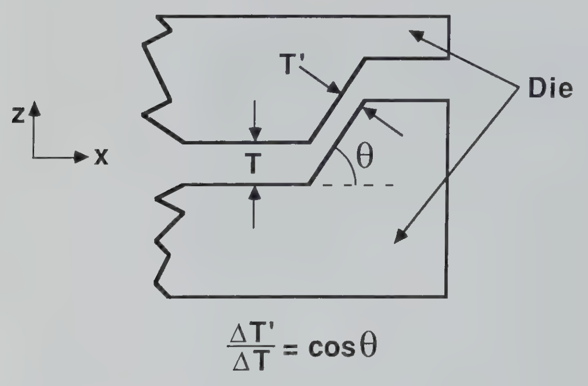

Figure 10. Die-gap variation versus sheet thickness in matched metal die with slanted surfaces.

2.5.5 Forming Cycle Times The typical components that make up the total cycle time for forming thermoplastic composite parts using matched-metal-die press forming are shown in table 6. As the table indicates, cycle times that have been achieved during development for LDF® sheet forming are 52 to 57 minutes. The bulk of this time is used in heating and cooling dies, which have to be at the same temperature as the melted resin. No attempt was made to reduce the high thermal inertia of the existing dies used to generate this data or to improve the heat transfer rate. Several techniques or concepts for reducing the thermal inertia of molds are under development. One such example is a concept being developed by Intellitec Corporation of Massachusetts, which relies on electrically heating only a thin layer of conductive composite cast on the surface of the mold to maintain the surface at the molding temperature. When the electrical power is turned off, the rest of the mold acts as a heat sink and quickly quenches the surface layer to a lower temperature. Some of these have been looked at in the past with respect to injection molds without much success, due mainly to mold structural problems. However, since the pressures used for thermoplastic composite forming are not expected to be as high (100 to 500 psi versus 1000 to 10,000 psi for injection molding), use of low thermal inertial molds is already becoming a reality [13]. With optimized die heating and cooling, it is expected that the total cycle in this case can be reduced to 3 to 18 minutes. In forming continuous inextensible fiber composite sheets, the primary modes of deformation are bending of the fibers, where the local strains are small, and squeezing flow, where the stresses are compressive. The level of deconsolidation during forming is therefore small or absent. For this reason, lower forming and consolidation temperatures and pressures have been used successfully, resulting in lower cycle times because the need to heat and cool dies is reduced. Hence, in this case the cycle time is of the order of 2 to 7 minutes. With some optimization this can be brought down to about 1 to 2 minutes. In contrast, the drawing deformation mode in LDF® sheets requires a high temperature because the drawing stresses are directly related to the resin viscosity [2]. Also, during drawing, the sheets tend to deconsolidate much more than in non-drawing deformation; hence higher temperature and pressure and/or longer times are required for re-consolidation. In all the above cases, however, the optimized forming cycle times should pave the way for economical forming of thermoplastic composites. Similar cycle times are achievable in hydroforming and rubber-pad forming. Diaphragm and autoclave forming, which require heating and forming in pressurized vessels, might not lend themselves easily to rapid heating and cooling. In this case, the ultimate cycle times might not be that different from the 60 minutes discussed in Diaphragm Forming, section 2.3.2.

Table 6. Cycle times—matched metal die press forming (mins)

	Current Experimental		Expected Optimized	
	LDF®	Woven fabric (cont. fiber)	LDF®	Woven fabric (cont. fiber)
Die heat-up	30	0	1–10	0
Sheet heat-up	1–5	1–5	1	1
Transfer to dies	.01–.05	.01–.05	.01	.01
Deformation	.1–.5	.1–.5	.1–.5	<.1
Consolidation	1	1	0–1	0–1
Die cool down	20	0	1–5	0
Total	52.1–56.6	2.1–6.6	3.1–17.5	1–2.1

2.6 Deformation Analysis: Mechanics

Whether or not a given part can be formed successfully depends to a large extent on the deformation mode the particular sheet being used for the forming is capable of withstanding without failure. Failure is defined broadly as unintended fiber placement (generally resulting in wrinkling and tow splitting) or breakage in the formed part. Part geometry, therefore, determines the suitability of the sheet. In addition, the forming process used might impose certain restrictions in the deformation path that could cause failure or an unacceptable part. For example, a part that is successfully formed using a diaphragm forming technique might not be similarly formed using matched-die press forming. Process analysis to help guide the design and tooling for a part and the selection of a forming system before hardware is actually fabricated and installed is highly desirable to reduce process development cost.

To aid analysis, one can think of the sheet forming process as a geometric or spatial transformation of a sheet preform to the shape of dies, with the path of the deformation determined by the dependence of the behavior of the sheet on the loading characteristics of the forming system (see fig. 11). The output of this process is a specific fiber structure or placement in the formed part. To control the sheet forming process, therefore, one needs to understand the relationships among material forming behavior, the loading conditions inherent in a given forming system, and the geometric constraints imposed by the part design. The most critical element in establishing this relationship is the material response to load, which is described by its constitutive equation. Unfortunately, this is the area in which the least is currently known. However, constitutive equations for high-temperature deformation of advanced thermoplastic composites are slowly emerging [15–17].

To analyze forming in the past, assumptions have had to be made about material behavior. In continuous fiber composites, the simplest case is to assume a transformation route in which the material behavior is ignored except for the geometric constraints imposed by the inextensibilities of the reinforcing fibers. This approach comprises the "kinematic analyses" that have been used in most of the deformation analyses so far reported in the literature [6–8]. A hemisphere is used in most of these cases because it lends itself more easily to mathematical manipulation than most of the complex 3-D shapes formed in practice. The most successful application of this approach is with the fiber structure in woven fabrics, which, as a result of the restricted fiber movements due to the weave, enables further assumptions that allow relative mapping of the individual fiber bundles on the surface of a hemisphere.

Results of some of these kinematic analyses have provided useful insights in developing forming processes for actual forming situations. Examples involve the comparison of a unidirectional fiber tape and a woven fiber tape, estimation of thickness distribution in formed parts, and differences between continuous and discontinuous fiber systems [9,11]. The analyses, although idealized, enable the exploration of the implications of certain material deformation behaviors to be explored. They have shown that non-uniform thickness distributions will most likely be present in 3-D shapes. This means that in matched-metal die forming, dies designed to uniform thickness will produce either unconsolidated sections, due to lack of pressure from rigid tools, or

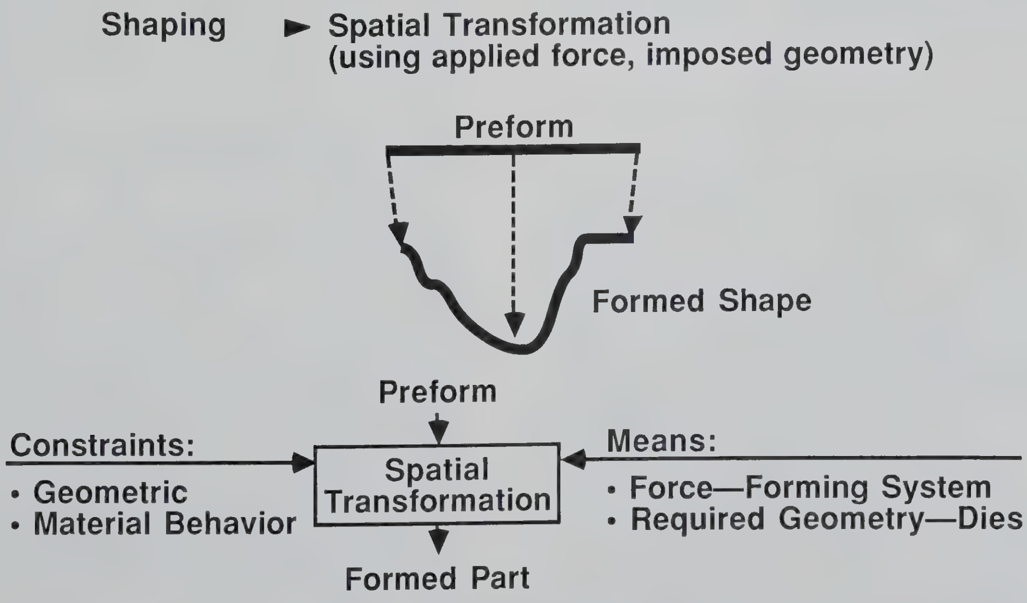

Figure 11. Elements of shaping (forming).

resin-rich areas due to resin squeeze-out from thicker to thinner sections, resulting in non-uniform fiber volume fraction distribution. This makes forming with at least one half of the tool flexible highly desirable. Diaphragm, autoclave and rubber-pad forming, therefore, seem better for consolidation purposes than matched-metal die tooling.

The ultimate location of the fiber filaments and the resultant thickness distribution in a formed part are controlled by the material deformation behavior and the loading path imposed by the forming system. In matched-metal die press forming of, say, a hemisphere, the preferred loading scheme is to clamp the sheet edges while pressure is applied to certain sections of the sheets by a punch (see fig. 1). Note that the clamping stress does not need to be continuous or uniform around the periphery of the part. This method increases the level of tensile stresses in the part to prevent wrinkling. However, due to the die geometry, the transverse stresses are also increased, resulting in transverse fiber sliding, especially in uni-ply or low inter-ply shear stress forming situations. Hence, continuous fiber composites, with high inter-ply shear stress, as in woven fabrics, tend to be more suitable for forming in matched-die press forming. For diaphragm forming, uniform pressure over the whole sheet and shear loading on the outer plies due to the diaphragms enable some control of lateral fiber displacements, as discussed in the previous section. Hence uniform thickness distributions are possible for a simple shape like a hemisphere [13]. However, other shapes and different pressure profiles result in severe lateral fiber displacements (see fig. 7).

2.7 Summary of Current Practices

The preceding discussions on the state of the art can be summarized into the following guidelines:

2.7.1 Sheet Selection For applications with parts of gentle curvature and not requiring high mechanical properties, woven fabric, preferably a fine weave, is used. When a multi-ply unidirectional tape is used, an unconsolidated laminate with the individual impregnated layers (uni-plies) reduces inter-ply interaction and hence is better in most forming situations. However, handling problems may make its use difficult. For parts requiring draw, especially in multi-cavity (repeated sections) as in beaded panels, the LDF® sheet structure is most suited.

2.7.2 Forming Method Press forming is the simplest and usually the most readily available, so it tends to be the first choice. In using matched-die tooling, it is preferable to make one half of the tooling flexible to aid uniform part consolidation. Matched-die press forming seems to be most suitable for woven fabrics. Diaphragm forming (this may apply equally to autoclave forming) has been shown to provide excellent control of fiber placement in certain classes of geometries, such as a hemisphere, when used for multi-ply continuous fiber sheets.

2.7.3 Forming Conditions The resin in the sheet should generally be at melt temperature during forming or shaping, especially for LDF® sheets. After shaping, a consolidation pressure is required over the whole part surface until it is cooled to below the resin T_g. Sheet clamping or a means of providing tensile stresses in the sheet during forming is necessary to minimize wrinkling.

2.7.4 Tool Design Considerations for tooling are generally the same as for sheet-metal forming dies or compression molding. However, tool contact with the deforming material should be in such a way as to maximize uniform pressurization of the sheet surface at all times. This reduces lateral fiber displacements due to squeeze flow.

3. Review of Current and Potential Applications and Markets

In this section, current and potential future applications of thermoplastic composite sheet forming in the composites industry are reviewed. Almost all of these are in the military and aerospace markets. The cost savings motivation that is driving these programs is presented to put things in perspective.

3.1 Current 3-D Part Applications in Military and Aerospace Markets

The variety and complexity of parts that can be made using sheet forming is virtually unlimited, although the quality of very complex parts will be determined by the material form and the forming system used. This perception is guiding the composites industry, which now seems to consider almost any part a candidate for sheet forming. In reality, however, as the size of the part to be formed gets bigger (such as wing skins), some forming techniques, such as press forming, become impractical as a result of the size of presses needed.

As mentioned earlier, thermoplastic composite sheet forming is relatively new. This, coupled with the lack of a significant database on material performance, means that in the military and aerospace industries there are no significant production-scale thermoplastic composite structures currently flying on aircrafts. The most advanced application programs involve prototype parts that are undergoing flight tests but are not slated for production. Discussions on applications in these markets are therefore limited to potentials. The largest part of the application work is driven by government funding. The best source of information on these potential applications is the annual Government/Industry Review of Thermoplastic Matrix Composites sponsored by the Material Laboratory of the Air Force Wright Aeronautical Laboratories. For aircrafts, these applications can be grouped into three broad categories: (a) under skin structural elements, (b) skin structures (including doors, flaps, spoilers, etc.) and (c) interior panels and structures. Most of the ongoing applications that the author is familiar with are in category (b), with a few in (a). No major activities seem to have been published under category (c).

Virtually all of the programs that currently involve flight tests of thermoplastic composite parts are skin-type structures, and since the information on them has been presented only in closed sessions at the Government/Industry Review meetings, they cannot be described in this paper.

3.2 Potential Applications in the Military and Aerospace Markets

Whereas past applications involving skin-type structures reflect very conservative use of advanced thermoplastic composites, current programs are much more ambitious and complex in nature. The approaches taken bring out the real potential of thermoplastics, especially in the area of cost savings, and insights gained from the earlier programs have no doubt contributed to these developments. Three of these potential programs that have been discussed in the open literature are summarized below.

3.2.1 F/A-18 Vortex Spoiler McDonnell-Douglas and ICI/Fiberite are fabricating a vortex spoiler, or lex fence, used to reduce the turbulence and hence vibrations, for improved fatigue life in tails of the F/A-18 aircraft. It is made of APC-2®/AS4 unidirectional tape. The thermoplastic composite part is expected to save about 20 pounds per aircraft over the incumbent aluminum part. The potential for this application is 700 to 800 shipsets [14].

3.2.2 Westland Tailplane Section Westland designed and manufactured a thermoplastic composite tailplane for the Westland 30–300 helicopter to demonstrate the feasibility of reduced manufacturing costs of thermoplastics over thermosets. All the thermoformed articles in this assembly (either PEEK or PEI) were press formed in matched-metal tools [21]. These were leading and trailing edges and skins for bonding onto Nomex® honeycomb cores. The program demonstrated both weight and manufacturing cost savings of the thermoplastic tailplane assembly.

3.2.3 Boeing Prototype Access Door In this program, Boeing utilized Phillips' PPS/woven carbon fabric sheet to produce a prototype access door with 25% and 67% weight and cost savings, respectively [22].

3.2.4 Proprietary Programs Besides the programs discussed above that are available in the literature and those presented at closed government sponsored meetings, a number of proprietary programs are ongoing between material suppliers and prime contractors interested in reducing this technology to practice. Such programs are probably going to have the greatest impact on determining the value of sheet forming and hence should be followed carefully as they become known.

3.3 Current Applications in Automotive and Industrial Markets

Not much is available in terms of the application of sheet forming of advanced thermoplastic composites in the automotive and industrial markets. The automotive industry seems to be less driven to these advanced materials but rather by lesser performance materials such as random fiber reinforced thermoplastics that are produced by compression molding-type operations. Overall, resin transfer molding seems to be the advanced composite processing technique that is receiving most attention in this market. The story is similar in the industrial markets where other processing techniques such as filament winding and pultrusion seem to be the approaches of choice. There is, however, no doubt that progress made with this technology will find its way into these markets, especially as material and processing costs go down.

3.4 Cost Savings Motivation

As was stated at the beginning, probably the most important force behind the drive to develop thermoplastic composites is lower manufacturing cost. Most of the developed programs that have been approached from this basis have indeed demonstrated the cost savings aspects of sheet forming. The basic ingredient in all this is that when parts are designed from scratch with a thermoplastic composite mindset, more often than not the ability to consolidate a number of pieces into a single, formable complex part goes a long way in bringing part acquisition costs down. With this in mind, the application programs have tended to concentrate on structures that lend themselves easily to parts consolidation and tend to incorporate integral stiffening. These have included bulkheads, stiffened ribs, fairings and skin panels, and support beams.

4. Limitations of Current Technology

The previous section indicates that formed structural thermoplastic composites are not yet in full-scale production in any application. There are several reasons for this. The first is not limited to sheet formed thermoplastics but is related to the inertia associated with using a new material system. The database on thermoplastics is not as extensive as that on thermoset composites; hence, there is not much confidence in their use as replacements for thermoset composites and/or metals. The cost associated with qualifying new material systems for use in the aircraft and aerospace industry is huge and tends to act as a barrier to quick adoption. For thermoplastic composites to be considered, the effort devoted to generating A- and B-basis allowables has to be increased tremendously.

From sheet forming aspects, the key limitations of current technology include:

- Lack of commercial quantities and high cost of sheet preforms
- High upfront development cost due to lack of predictive capabilities for sheet forming behavior
- High tooling cost
- Absence of quality assurance techniques to measure fiber placement, consistent quality
- Long cycle times for processing due to high temperatures
- Joining techniques
- Lack of extensive database on formed part performance, viscoelasticity

4.1 Lack of Commercial Quantities and High Cost of Sheet Preforms

Similar to thermoset composites, thermoplastic composites are generally available on the market in the form of pre-consolidated tape or multi-ply sheets, where the resin has already been combined with the reinforcing fibers. The current cost of these preforms for sheet forming is very high because (1) the processes for combining the resin and fibers are expensive, and (2) the current market section is so small that the lower cost associated with economies of scale is not yet possible. Since material suppliers are not sure of the long-term demand for their materials, the rationale for building large-scale production facilities that would reduce preform production cost is not there. Hence, preforms are being produced and marketed in developmental quantities and generally not readily available. The exception to this lack of availability is probably APC-2®.

4.2 High Upfront Development Cost Due to Lack of Predictive Capabilities for Sheet Forming Behavior

Demonstrating the capabilities of structural thermoplastic composite parts involves forming actual parts. In general, the development cost associated with such undertaking is very high, especially in the fabrication of tools. Thermoplastic composite forming involves high temperatures and pressures. This combination means that most of the low-cost tooling concepts currently being practiced for thermosets cannot be used (see Forming Tools, sec. 2.4). Tools fabricated for demonstration work are the same as production tools and cannot be justified in cases when only one or two demonstration articles are desired. The level of understanding of forming dynamics is limited, and there are no predictive capabilities available to pre-engineer tooling or to select a forming technique that minimizes the trial-and-error approach now being used which increases development cost. Good predictive capabilities should enable the prediction of fiber placement and part consolidation level in any forming technique and tooling of interest. In practice, forming techniques have not been developed enough to control fiber placement during forming and to ensure uniform thickness and good consolidation.

4.3 High Tooling Cost

As has been discussed all along, tool cost is very high. The need for low-cost tools to allow forming demonstration to evaluate this technology is very urgent.

4.4 Absence of Quality Assurance Techniques to Measure Fiber Placement, Consistent Quality

Quality assurance goes hand-in-hand with material property database (A- and B-Basis allowables) to increase the confidence level in using any material system in structural applications. In the thermoset industry, the two key quality assurance techniques are C-scan (to ensure part consolidation and no voids) and ply tracking (to ensure that all plies are present and in the orientation specified). When thermoplastics are formed, an additional technique is needed to determine fiber orientation distribution. During thermoset hand lay-up, once a ply is laid-up in a given orientation, there is usually little deviation from the expected or specified orientation over the whole ply surface. In sheet forming, even though the ply starts out from a known orientation, upon forming, the new orientation cannot usually be inferred with much certainty. In addition, this orientation can vary considerably with location even within the same ply. The only way to be sure of the fiber orientation in the final part is to measure it layer by layer. There are no known simple methods of doing this nondestructively. Even when the measurement is attempted destructively, methods, such as sectioning and taking micrographs, are time consuming and impractical for complex shapes. For thermoplastic composites to achieve widespread usage with confidence, determination of fiber orientation distribution is a must.

4.5 Long Cycle Times for Processing Due to High Temperatures

The promise of lower manufacturing cost for thermoplastic composites versus thermoset has been tempered by the requirement that these high-performance thermoplastics require extremely high processing temperatures. These high temperatures, along with the very high melt viscosities, have resulted in long processing times that seriously cut into the predicted cycle time advantage over long thermoset curing times. As indicated in Forming Cycle Times, section 2.5.5, the forming processing time for thermoplastic composites consists mostly of the time required to heat and cool tools or forming equipment to and from the high processing temperatures. These high temperatures require specialized equipment that was not available in the composites industry as recently as 8 to 10 years ago.

4.6 Joining Techniques

Despite the generally accepted notion that thermoplastic composites allow for parts integration over thermoset counterparts, a significant amount of assembly of sub-components is required to make certain large or complex structures. Such assemblies generally involve joining. In the thermoset industry, adhesive bonding and mechanical fasteners are the mainstay. However, there are some inherent disadvantages of thermoset adhesives, such as low solvent resistance and the extra weight associated with fasteners along with ply build-ups necessary for their use. Welding of thermoplastics promises to overcome these shortfalls but has not yet been fully developed. Some of the issues involved have been dealt with in recent publications and will not be covered here [23]. But it suffices to say that without cost-effective joining techniques, the full potential of thermoplastic composites will not be realized.

4.7 Lack of Extensive Database on Formed Part Performance, Viscoelasticity

The bottom line in raising the confidence level of designers in any material system is to log actual end-use service hours. As indicated in Review of Current and Potential Applications and Markets, section 3, some of it is being done on thermoplastic composites, limited mostly to secondary and noncritical structures on aircrafts. Some level of risk needs to be taken to start building this performance database for thermoplastic composites.

5. Needed Scientific and Engineering Solutions

The areas of thermoplastic composite sheet forming technology development where, it is believed, scientific and engineering solutions are in critical need have been grouped into five main categories. These are not the only areas that need addressing, but advancements made in them are expected to have major impact on the adoption of thermoplastic composite sheet forming in the composites industry. Each of these areas will now be discussed in more detail.

5.1 Database of Basic Material Forming Behavior

As is the case with the introduction of any new material system, thermoplastic composites have gone through the initial phase of determination of worth. All the developmental programs that have been discussed earlier suggest that this material system is viable both from performance and production cost standpoints. To optimize the manufacturing of parts, the material behavior during forming needs to be understood. In particular, a constitutive relation needs to be determined for each of the material forms discussed in section 2. Measurement techniques or systems, such as the Rheometrics Dynamic Mechanical Spectrometer, which has played a key role in measuring fundamental rheological properties of thermoplastics, need to be developed along with the necessary theories or relations to translate them to actual forming situations. Under certain assumptions, it has been shown that two or three independent material properties are necessary to describe the deformation behavior of the material forms of interest here [15–17]. These, of course, need to be verified experimentally and then be applied to modeling of three-dimensional forming. Finite element modeling (FEM) is going to play a vital role in this endeavor and the need for commercial FEM codes in this area cannot be overemphasized.

In addition to the basic material properties, criteria need to be developed to establish quantitatively when a part quality, such as extent of wrinkling, is unacceptable. Such criteria will help guide the development of new material forms, equipment and process techniques.

5.2 Thermoplastic-Based Part Design—Not Thermoset Substitute

To maximize the benefits of using thermoplastic composites, parts made from them have to be designed from scratch to capture all the advantages and avoid their limitations. It is believed that one of the key advantages of thermoplastics over thermosets for cost savings is the potential for parts integration. However, most of the applications to date for thermoplastics have been nothing more than a direct one-to-one replacement for existing thermoset composite or metal parts. These usually impose limitations on design flexibility, which is required to optimize the benefits from going to a thermoplastic part [24].

5.3 Integration of Database With Analysis Techniques

In a well-consolidated composite part (that is, no voids), the fiber structure (orientation, aspect ratio, etc.) determines to a large extent most of the mechanical properties of the final part. In hand lay-up thermoset composite processing, the limitations of the accuracy of fiber placement are fairly well understood, and fiber orientation specifications during design are constrained by these limitations. However, once a given orientation is called for, as long as that ply is not left out during lay-up, one can generally be fairly confident of this orientation not changing during the curing process. In thermoplastic composite forming, the deformation involved in the shaping process changes the fiber structure from a known initial state. Even when this new state can be determined (see next section), this structure will vary with position. Structural analysis for formed parts will, therefore, be more complex and have to be tied to the manufacturing and part design processes in a computer aided engineering (CAE) environment, more so than has been required for thermosets. Here also the need for commercial computer software and hardware is obvious.

5.4 Post-formed Part Analysis Techniques

As indicated in the previous section, one of the key NDE techniques that will be required for formed parts is one for determining fiber orientation distribution. This is because the changes in thickness and fiber orientation distributions on forming from a known initial state cannot yet be predicted with any certainty. Therefore, from a reproducibility standpoint each part inspection has to include fiber orientation determination. None of the known NDE techniques currently used for composites (e.g., C-scans) has been shown to provide such information. Measurement and analysis techniques and equipment need to be developed to quantitatively provide this information as a vital input to the processing-structure-property relations for formed composites.

5.5 Low-Cost Tooling Concepts

The high temperatures and pressures required for forming thermoplastic composites present challenges in terms of tooling design and the choice of tool material. As anyone familiar with the metal forming and thermoplastic molding industries knows, tooling cost is usually quite high (tens to hundreds of thousands of dollars). When the production lot size is small (as is expected to be the case for most of the anticipated near-term applications of formed thermoplastic composites), tool cost can become a significant portion of part production cost. The need for low-cost tooling approaches, particularly suited to small production lot sizes, is high.

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Off-Line Programming for Composites Fiber Placement

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Automated construction of composite material parts involves the planning and execution of complicated geometrical movements by computer controlled machines. Ideally, such motion sequences can be planned and simulated somewhat automatically from a CAD description of the part to be manufactured, and operator input. Such a CAD-based system would alleviate very tedious manual teaching of motion sequences that is sometimes now required. This article describes some of the geometrical and other problems which a CAD-based system must solve.

Key words: close out; filament winding; friction steering; geodesic path; natural path; off-line programming; simulation; tape laying.

1. State of the Art

We define an **off-line programming** (OLP) system as a machine programming language which has been sufficiently extended, generally by means of computer graphics, that the development of machine programs can take place without access to the machine itself. Off-line programming systems are important both as aids in programming present day industrial automation as well as platforms for research and development. Numerous issues must be considered in the design of such systems, such as the spatial representation of solids, graphical rendering of these objects, automatic collision detection, incorporation of kinematics, path planning, and dynamic simulation, simulation of sensors, concurrent programming, translation by post processors to various target languages, and workcell calibration.

Currently, OLP systems for programming industrial robots are beginning to enter the industrial market. These systems are being extended to simulate and program other factory machines such as coordinate measuring machines, NC machines, automated guided vehicles, and composite manufacturing equipment. Observing the recent history of the robotics market and usage of such systems may yield insight regarding the potential use of OLP for composite manufacturing.

In the last decade the growth of the industrial robot market has not been nearly as rapid as predicted. One primary reason for this is that robots are still too difficult to use. A great deal of time and expertise is required to install a robot in a particular application and bring the system to production readiness. For various reasons, in some applications this problem is more severe than others, and hence, we see certain application areas (e.g., spot welding and spray painting) being automated with robots much sooner than other application domains. It seems that lack of sufficiently trained robot system implementors is limiting growth in some, if not all, areas of application. At some manufacturing companies, management encourages the use of robots to an extent greater than that realizable by available applications engineers. Also, a large percentage of the robots delivered are being used in ways which do not take full advantage of their capabilities. These symptoms indicate that current industrial robots are not easy enough to use to allow successful installation and programming in a timely manner. In the case of automated composite manufacturing equipment (machines quite similar to industrial robots), we encounter a class of geometric and programming problems which are by no means simple.

The machines currently in use for automated composite manufacturing fall into perhaps three categories.

"Filament winders" are machines which wrap composite fibers around parts which usually exhibit some form of rotational symmetry. Although several various styles of filament winders exist, the most typical appears similar to a lathe, with the part formed by wrapping fibers on a mandrel form. The mechanism delivers fibers onto rotating mandrel by means of a dispenser often called a "payout eye." The payout eye is maneuvered spatially by a mechanism consisting generally of 2 to 4 degrees of freedom.

"Tape layers" are machines which lay strips of pre-formed composite tape in which all the fibers run uni-directionally along the length of the tape. These machines are often constructed like a gantry which manipulates a "tape head" which dispenses the tape onto the layup surface. Such machines typically have 5 degrees of freedom.

"Industrial robots" are being considered for use in composite tape lay up. In this case a conventional industrial robot is fitted with a tape head end-effector. The resulting system performs much the same (in theory) as a dedicated tape laying machine. Robots used for this application would generally have 5 or 6 degrees of freedom.

A common argument raised in favor of OLP systems is that their use helps avoid the use of production equipment when it needs to be reprogrammed, and hence, automated factories can stay in production mode a greater percentage of the time. They also serve as a natural vehicle to tie computer aided design (CAD) databases used in the design phase of a product's development to the actual manufacturing of the product. In the case of OLP for automated composite manufacturing, the direct use of CAD models of the layup surface or mandrel to automatically plan fiber paths and patterns provides the major incentive for their application.

1.1 Usage of OLP for Composite Manufacturing

The basic steps that the user of an OLP system might follow in order to create a program for a filament winder or tape layer are as follows:

1. Obtain the CAD model of the mandrel or layup surface.
2. Prepare the surface data for computations and display.
3. Specify individual filament circuits or tape courses, or use pattern generation features to specify winding patterns or tape laying patterns.
4. Verify lap/gap constraints and investigate the "filament strain" in non-perfect tape lays.
5. Convert filament circuits or tape courses into motion of the payout eye or tape head.
6. Create the program sequence and simulate.
7. Post-process and download program(s) to the physical machine.

In addition, as the patterns are planned by the system, a large database of information can be stored and made available for query by the user or by another program—for example, a finite element analysis could be done be querying the database and requesting the relevant information.

Let's briefly consider each of the above steps before getting into details.

1.1.1 Obtaining CAD Models and Surface Preparation CAD models which make up the mandrel or layup surface can come from any of a variety of sources:

1. An IGES file created on any external CAD system supporting IGES (a "neutral file" format which virtually all CAD system vendors currently support).
2. A file from a particular vendor's CAD system in native format. In this case the OLP system must have a special translator for this format.
3. A CAD model constructed "locally" using the CAD functionality of the OLP system.
4. An ASCII file of data from a digitizer. In this case the OLP system must be able to construct a surface model from this data.

It is quite likely that to obtain a CAD model of a mandrel, it may need to be assembled from various components; for example, the end domes may come from a source different than the interior of the mandrel. An OLP system needs to support such assembly operations.

In the case of tape laying, the user needs to be able to specify a **region** of interest on the layup surface. This allows various subsets of the total layup surface to be considered by the system as separate entities. Regions can be specified by graphically picking (i.e., using a mouse pointing device to point at the surface) a closed contour on the layup surface. Alternatively, these region boundary curves could be created on any external CAD system which can be interfaced with the OLP system.

1.1.2 Computation of Filament or Tape Paths At the heart of the path computation algorithms is the ability to compute a **geodesic** space curve lying on an arbitrary surface. In the case of tape-path computation, a special kind of path that we will call a "minimum strain path" should be computed. Minimum strain paths are similar to geodesics when the curvature of the surface is low. We will define terms and describe these algorithms more fully in a later section of this report (taken from [1]).

As paths are computed, the CAD model of the surface can be updated to account for the thickness of the filament band or tape. This computation might be skipped if the user has indicated that the tape or band thickness is zero. If the mandrel is non-convex (i.e., is not completely convex) then any bridging of the filaments in winding should be detected. This checking will be skipped if the user has indicated that the mandrel is a convex solid.

1.1.3 Pattern Generation In filament winding on surfaces of revolution, the user will be able to specify hoop or helical winding patterns. In the case of helical patterns, the user will specify a close-out curve and a desired winding angle, and the system will compute a set of possible patterns and resulting winding angles. For example, if the user requests a winding angle of 40°, the system may respond with several choices:

1. Side by side pattern possible at 48.2°.
2. 3-point star pattern possible at 36.5°.
3. 9-point star pattern possible at 40.8°.

Figure 1 shows an end-on simulated view of a mandrel after just a few circuits of filaments have been applied. In this case a pattern is developing which appears to have three lobes of "points". Hence, terms like "3-point star" have arisen to describe such patterns. On the same mandrel shape, subtle changes in winding angle can result in very different types of star patterns to emerge.

In the case of hoop patterns, the user specifies the minimum and maximum positions along the axis of the mandrel and the hoop pattern is calculated to cover the mandrel between those positions. In both hoop and helical pattern calculation, a user-supplied value of surface friction is used to ensure that the patterns are physically possible without fiber slippage. This limited friction implies that for some mandrels, hoop patterns will not be possible, and likewise, helical patterns at certain winding angles will not be possible.

In tape laying, the user is able to specify a close-out line perpendicular to the direction of the tape lays along which the tape pattern will "close-out" (i.e., have zero lap-gap). The user may specify a variety of patterns. The available patterns will be analogous to patterns achieved by filament winding (i.e., side-by-side, 5-point star, etc.). In any of these patterns other than the simple "side by side," the user has the opportunity to specify an angular parameter which sets the angle between the two orientations of tapes that are woven to create a single ply.

Figure 2 shows simulated views of a region of a surface which is being tape laid in a certain pattern. Figure 2a shows how the pattern is emerging after six tapes have been laid. Figure 2b shows the complete pattern.

1.1.4 Verification of Lap-Gap Constraints Users will be able to specify maximum allowable laps and gaps. Any neighboring tape lays which violate these bounds could be indicated graphically with highlighting. Additionally, users should be able to plot a graph of lap-gap versus tape length for any two neighboring tapes to inspect the quality of the layup. Similarly, graphs of tape "filament strain" versus tape length can be requested.

1.1.5 Tool Path Generation Having computed paths on the mandrel or layup surface, these can be transformed into paths of the payout eye or tape

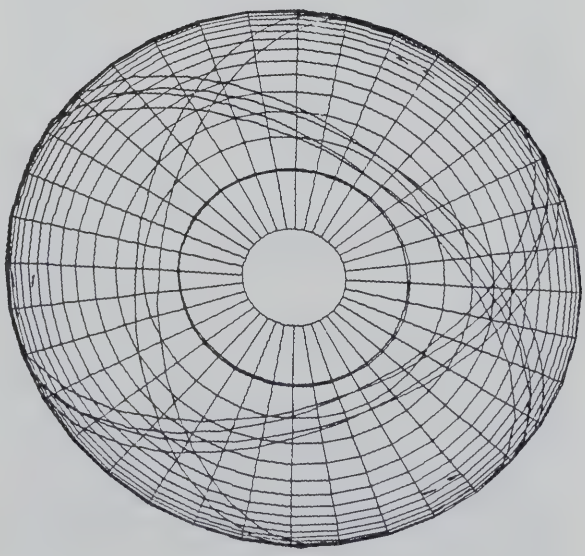

Figure 1. End-on view of a simulated 3-point star pattern after a few circuits of filaments have been applied.

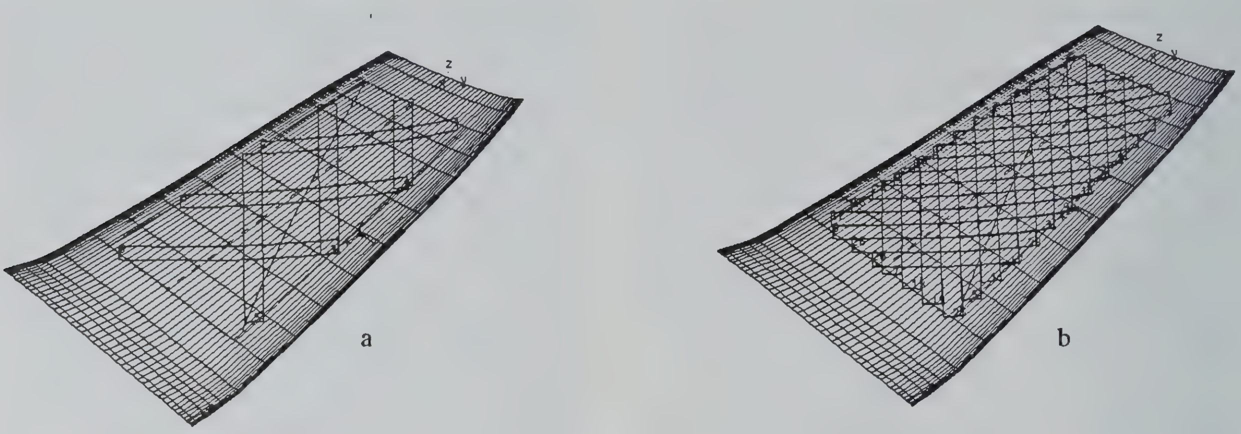

Figure 2. Simulation of tape-laying on a surface after six tapes have been laid (right) and the complete pattern (left).

head (in general, we will call the terminal effector the tool). For filament winding machines, the tangent length to be used can be specified as a general function of position along the mandrel's axis. The simplest such tangent length function is the case of constant tangent length. Computation of the tool motion can often be somewhat machine specific as the available number and types of machine degrees of freedom must be known to perform such computations.

1.1.6 Create Program Sequence and Simulate Program creation will be quite straightforward in that having planned all the filament circuits or tape lays, a strict sequence has already been implied. Hence there is generally no need for the user of such an OLP system to actually "write" a program in the textual sense. Simulation may be performed of all or a portion of the machine's activities, or may be skipped.

1.1.7 Post-Process and Download Device Programs Resulting programs may be post-processed into the native language of the particular filament winder or tape layer being used. Support for new machines can be added as required. Some basic calibration procedures must be provided for ensuring that the simulated arrangement of machine and part matches reality. These calibration procedures generally involve using the machine itself to "teach" some fiducial points on the actual workpiece and for the user to indicate the same fiducial points on the CAD model of the same workpiece in the OLP system. By computing a correspondence (usually in the least-squares sense), the OLP system can ensure that its geometric model of the position and orientation of the layup surface relative to the robot is accurate.

1.2 Background: Surfaces, Curves, and Geodesics

A **surface** in the usual sense of the word is an object that exists in 3-D space, but may be characterized with two parameters. Hence, in choosing a point on the surface, one has two degrees of freedom. A surface is like an infinitely thin sheet of material twisting through space. In fancy terminology, a surface is a two-dimensional manifold embedded in three-dimensional space.

A **space curve**, or simply, a **curve** in the usual sense of the word is an object that exists in 3-D space, but may be characterized with a single parameter. Hence, in choosing a point on the curve, there is just one degree of freedom. A curve is like a infinitely thin thread winding through space. A curve is a one-dimensional manifold embedded in three-dimensional space.

Given a surface, there is a class of space curves (let's call them **embedded curves**) which lie completely in (or on) this surface. Such embedded curves can be described as one-dimensional manifolds embedded in the two-dimensional manifold of the surface.

A **geodesic** is an embedded curve with a special property which can be stated in several ways:

1. Arc-length definition: The embedded curve connecting any two points on the surface which has the minimum path length is a portion of a geodesic of the surface.
2. Kinematic definition: A particle moving along a geodesic has an acceleration vector which always lies in the plane spanned by the particle's velocity vector and the local surface normal. Another way to state this is that there is no acceleration "side-to- side" in the surface—acceleration is only used to keep the

particle in the surface (or to speed up and slow down along the path).

3. Static force definition: For the case of a convex surface, a "thread" stretched over it under tension is in static equilibrium only if it lies along a geodesic of the surface. Only in this case are there no sideways forces that would cause the thread to slide sideways on the surface.

1.3 The Curvature of Surfaces

A surface whose surface normal vectors point in the same direction at all points on the surface is said to be flat. In the more general case, the rate at which the direction of the surface normal changes as you move across the surface gives its curvature.

Given a point on a surface, p, and a direction of motion on that surface, v, the curvature of the surface in that direction is a single number, $k(p,v)$. To completely describe the curvature of a surface at a point of interest requires the specification of two **principal curvature directions,** v_{min}, v_{max}, and the two corresponding principal curvatures, k_{min}, k_{max}. It can be shown that these directions are always orthogonal, and that the two curvatures represent the minimum and maximum curvature of the surface at that point. From the principal directions and curvatures, the particular curvature in any given direction can be computed [2].

The **Gaussian curvature** is a property of a point on a surface and may be computed as the product of the two principal curvatures,

$$K = k_{min} k_{max}. \tag{1}$$

We will call a surface **doubly-curved** if $K \neq 0$, that is, if both principal curvatures are non-zero. We will call a surface **singly-curved** if $K = 0$ except for the special case of both $k_{min} = 0$ and $k_{max} = 0$ in which case the surface is said to be flat.

1.4 Isometric Surfaces

Two surfaces, A and B, are said to be **isometric** to one another if each point in surface A can be put into correspondence with a point in surface B with a one-to-one mapping such that distances measured in the surface are preserved. If two surfaces are isometric to one another, certain geometrical features (called **isometrically invariant features**) are equivalent in the two surfaces. An important isometric invariant is the Gaussian curvature, K.

Surfaces which are isometric with a planar surface are of special interest to us. Such surfaces are called **developable** and have the property that they can be deformed to planar shape without changing any length measurements with the surface (i.e., no "wrinkling, folding, or stretching") [3]. The curved portion of a cylinder is an example of a surface that can be deformed to a plane in this way.

1.5 Natural Paths, Minimum Strain Paths, and Tape-Laying

The composite tape-laying geometrical problem is concerned with the placement of composite material tapes on various layup surfaces. In this section we give a few fundamental definitions related to tapes.

A **tape path** is defined by specifying the embedded curve of the tape's centerline on the surface along with the tape width. That portion of the surface which is covered by the tape is called the **image** of the tape on the surface.

We define a **natural path** as a tape path which has the property that the tape's centerline follows a geodesic and the surface has zero Gaussian curvature everywhere in the image of the tape on the surface.

For a tape (a section of a flat plane) to be laid on a surface without "wrinkling, folding, or stretching," the surface onto which it is laid must be isometric to the plane. Since the Gaussian curvature of the plane is zero, a perfect tape lay is only possible when the layup surface has zero Gaussian curvature. Therefore, a natural tape path only exists when the portion of the layup surface covered by the tape path (the image) is either flat or singly-curved. Further, if the tape is considered stiff laterally, then the centerline must follow a geodesic of the surface—otherwise, the path contains some tangential curving which would attempt to bend the tape laterally. If a tape follows a natural path, then the unidirectional composite fibers are not required to be under any strain.

With our definition, natural paths do not exist over any portion of a surface which is doubly-curved. However, as a practical matter, such surfaces will nevertheless be considered for tape layup. In an OLP system, the user can be alerted automatically, and the differential filament strain can be numerically and graphically reported to the user. The designer's experience or empirical experiments will be relied on to determine how much filament strain can be tolerated in practice. Given that doubly curved surfaces often will be considered for tape layup, it is important that the OLP system be able to compute a **minimum strain path** which is a path for which the differential filament strain is minimized.

On a perfectly flat surface, there are infinitely many natural paths, namely all paths that are straight lines (i.e., geodesics). On a flat surface, a composite tape can be deflected only very slightly from a straight line path. Given this amount of deflection per unit length, OLP systems might be able to compute slightly non-straight paths if desired. Straight lines in a flat surface are geodesics of that surface, and it turns out that our statements above about natural paths extend to singly-curved surfaces where geodesics should be used for the tape centerline. A slight variation of the centerline off of a geodesic might be tolerated as described by the deflection per unit length parameter mentioned above.

In summary:

1. On flat surfaces, every straight path is a natural path.
2. On a singly-curved surface (such as the surface of a cylinder), natural paths exist whenever the tape centerline follows a geodesic of the surface.
3. On doubly-curved surfaces (such as the surface of a sphere), no natural paths exist, but paths called minimum strain paths exist which come as close as possible to being natural paths.

1.6 Geodesics in Filament Winding

The filament-winding geometrical problem is concerned with the placement of composite filaments on various mandrels.

A **filament path** is defined by specifying an embedded curve lying in the surface of the mandrel.

Considering the static force definition of a geodesic, it is clear why geodesics are important in filament winding. Imagine trying to wrap a mandrel with a frictionless surface with a filament. This difficult task would in theory be possible only if the filament path was exactly a geodesic of the surface.

Given the existence of friction on the surface of the mandrel, filaments can be made to follow paths other than geodesics. When friction is quite low, these paths are quite close to geodesics. In the extreme case of a "infinitely sticky" mandrel, filament paths can be arbitrary embedded curves on the surface.

Given a value, μ, of the coefficient of static friction acting between the filament and the mandrel surface, a **generalized geodesic** can be computed. A generalized geodesic uses a **steering function,** $s(t)$, which is bounded in magnitude by the static friction,

$$-\mu < s(t) < \mu, \tag{2}$$

in order to continuously steer the filament path relative to the geodesic. Generalized geodesics contain the case of true geodesic simply by setting $s(t)=0$ at all times. When μ is not known accurately, it should be underestimated to ensure that resulting filament paths can be realized without filament slippage on the mandrel surface [4]. Our mathematical development below will include $s(t)$ so that we may control the deviation from the true geodesic of the paths we compute.

1.7 Mathematics and Computation of Generalized Geodesics

The computation of geodesics is central to both filament winding path planning and tape path planning. In both cases, it is desirable to be able to compute a generalized geodesic which neighbors (in a controlled way) the true geodesic. In filament winding this allows additional flexibility if some mandrel friction can be counted on, and in tape laying this allows additional flexibility if tape can be characterized as having some lateral compliance.

1.7.1 Mappings from Parameter Space to Cartesian Space Let our surface of interest be defined parametrically where the parameter vector, Θ, is 2×1 with the elements denoted by u and v,

$$\Theta=\begin{bmatrix} u \\ v \end{bmatrix}. \tag{3}$$

Points in 3-space, X, a 3×1 vector, are given by the surface's evaluation function, $E(\Theta)$, as a function of the parameter values,

$$\dot{X}=E(\Theta). \tag{4}$$

The **Jacobian** matrix of partials defines the mapping between velocities in parametric space to velocities in Cartesian space as given by

$$\dot{X}=J(\Theta)\dot{\Theta} \tag{5}$$

where the dot represents differentiation with respect to time, and $J(\Theta)$, a 3×2 matrix, is given by

$$J=\left[\frac{\partial x}{\partial u}\ \frac{\partial x}{\partial v}\right]. \tag{6}$$

Differentiating eq (5) yields an expression for Cartesian acceleration of the a point moving in the surface as

$$\ddot{X}=J(\Theta)\ddot{\Theta}+\dot{J}(\dot{\Theta}). \tag{7}$$

1.7.2 Definition of Vectors N and B At any instant as a particle moves on the surface, the normal vector at its current location is given by

$$N=\frac{\partial X}{\partial u}\times\frac{\partial X}{\partial v} \tag{8}$$

where "x" denotes the vector cross product. The vector N is not necessarily a unit vector, but may be normalized if need be. For our purposes, we will construct a special vector, B, which is orthogonal to the particle's velocity vector and also orthogonal to the local surface normal, by

$$B=N\times\dot{X}. \tag{9}$$

1.7.3 Equation of a Geodesic From our kinematic definition for a geodesic, we have that

$$\ddot{X}^{\mathrm{T}}B=0 \tag{10}$$

where superscript T denotes the transpose (i.e., eq (10) is a dot product). From an analysis of static forces and the relationship between the kinematic and static force definition of a geodesic, it can be shown [3] that the generalized geodesic we seek is given by

$$\ddot{X}^{\mathrm{T}}(\hat{B}-s(t)\hat{N})=0 \tag{11}$$

where $s(t)$ is the steering function which takes on values bounded by $-\mu$ and μ, the coefficient of static friction. The "hats" in eq (11) indicate that the vectors have been normalized.

1.8 Computation of Generalized Geodesics

Equation (11) is a second order differential equation whose solution is a space curve $X(t)$ traced out by a particle moving along the geodesic. In order to deal with general surfaces, the only means of obtaining a solution is via numerical integration. We will adopt the policy of performing this integration in the parameter space of the surface (rather than in Cartesian 3-space), as this ensures that each calculated point lies exactly on the surface. Further, we will create a correspondence between "time" and arc-length in parameter space. That is, we imagine that the particle moving along the geodesic is moving at a constant speed (namely 1 unit/sec) in parameter space. Another way to state this is that we are adjoining the constraint

$$||\Theta||=1. \tag{12}$$

Since eq (11) is a scalar equation, the addition of eq (12) gives us our second equation so we can solve for the two unknowns, namely, the evolution of the parameters, $u(t)$ and $v(t)$.

We characterize the velocity vector in parameter space by the angle Ψ that this vector makes with the positive u axis, and in so doing, may write the velocity vector in parameter space as

$$\dot{\Theta}=\begin{bmatrix}\cos\Psi\\ \sin\Psi\end{bmatrix}. \tag{13}$$

It follows by differentiation that

$$\ddot{\Theta}=\begin{bmatrix}-\sin\Psi\\ \cos\Psi\end{bmatrix}\dot{\Psi}. \tag{14}$$

After some manipulation we may write the equation of the generalized geodesic as a system of three first order equations as

$$\begin{aligned}\dot{\Psi}&=\frac{-(\hat{B}-s(t)\hat{N})^{\mathrm{T}}\,\dot{J}(u,v)\left[\begin{smallmatrix}\cos\Psi\\ \sin\Psi\end{smallmatrix}\right]}{(\hat{B}-s(t)\hat{N})^{\mathrm{T}}\,J(u,v)\left[\begin{smallmatrix}-\sin\Psi\\ \cos\Psi\end{smallmatrix}\right]}.\\ \dot{u}&=\cos\Psi\\ \dot{v}&=\sin\Psi\end{aligned} \tag{15}$$

As shown in eq (6) the elements of J are those of partial derivatives of the map from parametric space to Cartesian space. Likewise, the elements of $\dot{J}$ contain second partials of this map. Thus, at each step of the numerical integration process, the computation of the right hand side of eq (15) will involve querying the surface first and second partials.

1.8.1 Numerical Integration The generalized geodesic path on the mandrel or layup surface is computed from eq (15) with the use of a numerical integration routine, for example, a **fourth-order Runge-Kutta** algorithm with adaptive step size [5]. We suggest this choice because Runge-Kutta is well known as a stable, accurate, and efficient general purpose method of numerical integration. If extremely high accuracy is needed, perhaps the **Bulirsch-Stoer** method is favored. The other potential pitfall is if the equations turn out to be stiff, that is, if they contain two widely separated natural modes. In this case there are methods [6] which can handle these problems with better efficiency than Runge-Kutta.

1.9 Computation of Geodesics on Faceted Surfaces

The previous section discussed the computation of geodesics when first and second partials describing the surface's curvature are available. Given a faceted or mesh description of a surface, these partials can indeed be calculated using any of a variety of approximations. That is, the values of the first and second partials are computed for a particular location on the surface based on approximations computed from a set of mesh points (the vertices of the facets) that lie in the neighborhood surrounding the point of interest. In effect, there are several schemes by which an analytic surface can be fit to a neighborhood of points, and then the needed partials are computed from this analytic expression.

One must use care in creating this analytic surface from a set of mesh points. One cannot manufacture more information about the shape of the surface than one is given (in the mesh points). At one extreme in the spectrum of possible analytic models to use in fitting to the mesh is to use the faceted surface itself, and compute exact geodesics for the faceted surface! On faceted surfaces, geodesics (or any embedded curve) are piecewise linear space curves, and hence are completely described by an ordered list of points. Such a scheme to compute geodesics is attractive in that the computation can be cast as a geometric problem to which a solution can be found which requires no numerical integration. Hence, piecewise linear geodesics embedded on faceted surfaces can be computed efficiently.

1.10 A Related Two-Point Boundary Value Problem

Our entire discussion of geodesics so far is based on the notion that a tape lay or filament path will be specified by a starting point and a starting direction. Having defined these initial conditions for the differential equation, the complete geodesic is specified and may be computed.

It may be that a user would like to program a tape lay by giving desired start and end positions on the surface rather than a start point with direction. This constitutes a so-called *two-point boundary value problem* for which numerical methods of solution exist (namely the **shooting method** and the relaxation method). It is a significantly more computationally intense procedure.

1.11 Helical Patterns in Filament Winding

In this section we will only consider helical pattern generation for mandrels which are surfaces of revolution. Some ideas are based on the work reported in [2] and [7]. Pattern generation for more general mandrel shapes is feasible for OLP systems, but the algorithms needed are beyond the scope of this report. Also note that pattern generation for tape-laying can use most of the following methods.

It is interesting that geodesics on a surface of revolution have the following property: starting at a "close-out curve" at a certain winding angle, α, when the geodesic crosses the close-out curve having completed one full circuit, its winding angle will again be α. Hence, having computed one full circuit, subsequent circuits have exactly the same path shape, but are simply offset around the mandrel's axis. Let's call the offset angle ϕ_c, the radius of the mandrel at the close-out curve, r, and the band width, w, as shown in figure 3. At the close-out curve, the effective band width, w_e, is

$$w_e = \frac{w}{\cos\alpha}. \tag{16}$$

Exact close-out of winding patterns on general surfaces of revolution is rare. Usually the user wishes to specify a desired winding angle, α_d, at the close-out curve. A search for a winding angle which is close to α_d and which will cause close-out can be accomplished as follows.

Candidate winding angles a_i are computed so that the effective band width divides evenly the circumference of the mandrel at of the close-out curve. These values are

$$\alpha_i = \cos^{-1}\left(\frac{m\,w}{2\,\pi\,r}\right) \tag{17}$$

for all

$$m \in \{1,2,\ldots, m_{max}\} \tag{18}$$

where

$$m_{max} = trunc\left(\frac{2\pi\,r}{w}\right). \tag{19}$$

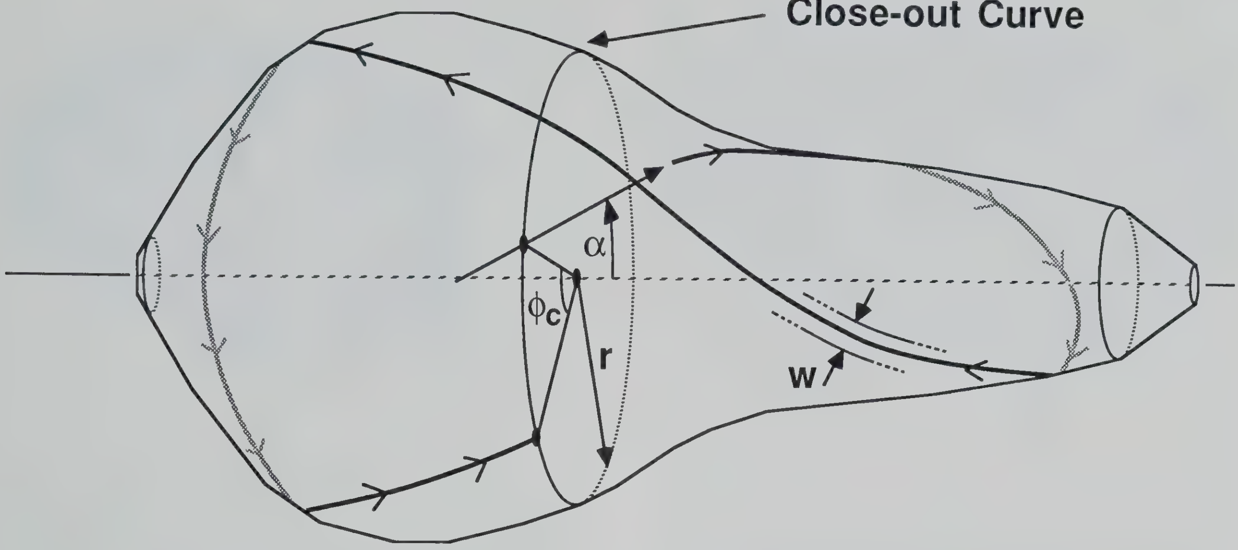

Figure 3. A circuit on a surface of revolution.

Amongst these candidate winding angles, search through them ordered by their proximity to the desired winding angle, and check if they will cause perfect close-out as follows.

Given a candidate α_i, compute the geodesic for one complete circuit and find the arc length of the precession about the mandrel axis as

$$s = r\phi_c. \tag{20}$$

Perfect close-out occurs if this arc length is a perfect multiple of the effective band width, e.g., if there exists an integer n such that

$$n\frac{w}{\cos\alpha} = s \tag{21}$$

and if n and m possess no common factor (we will call two integers which have no common factor **relatively prime**).

Since these conditions for perfect close-out will almost never occur, it is important that the OLP system pattern planner be able to offer patterns that nearly close-out. For example, close-out need not be perfect if it does not violate the lap-gap constraints that the user has specified. Such patterns that "nearly close-out" may be computed as a generalization of the above procedure. In the presence of friction on the mandrel surface, some steering may be used to create patterns that exactly close out and which do not cause any fiber slippage because friction constraints are respected.

Figure 4a shows a simple mandrel shape (in this case it is a surface of revolution). Figure 4b shows the resulting filament pattern which achieves perfect close-out using the algorithm described earlier.

2. Current and Potential Applications

The advent of OLP systems for automatic composite manufacturing seems to be mimicking that of OLP systems for industrial robots. The first suppliers of rudimentary OLP systems are the vendors of the actual machines. These vendors found that to sell their machines, they must supply at least rudimentary programming tools. As in the early days of robot programming systems, the user of automatic composite manufacturing machines has little choice but to use the programming software supplied with the machine. As with robot suppliers, these vendors generally are focused on selling their hardware, and are often not best suited to the development of CAD-based systems of the sophistication really needed. Hence in the case of the industrial robot, the machine vendors have not been the ones to develop successful OLP systems (a few minor exceptions exist). Rather, major CAD companies and small independent specialty companies were the ones to develop useful products aimed at OLP of industrial robots. In the case of automatic composite manufacturing machines, a similar evolution of OLP systems is to be expected.

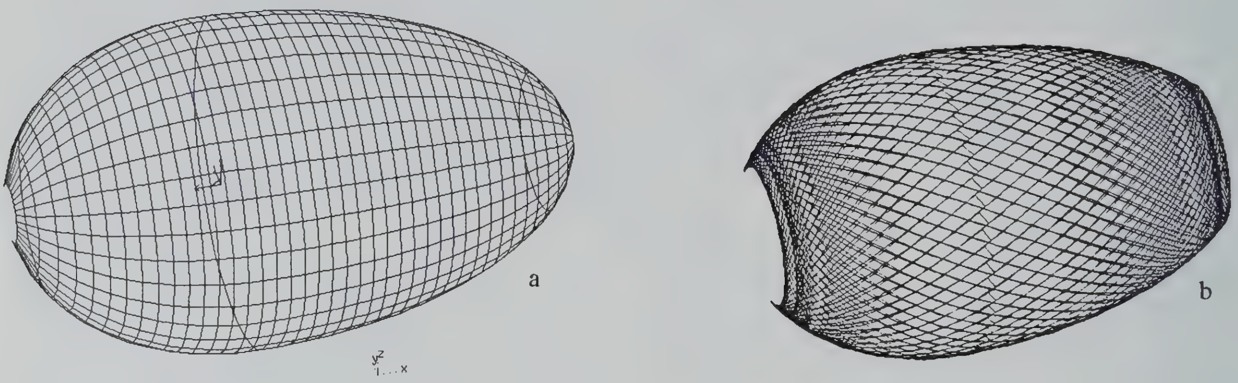

Figure 4. A simple mandrel (left) and the resulting filament pattern that achieves perfect close-out.

2.1 Current Applications

The majority of focus is on solving the problem of automated filament winders and automated tape layup by machine. Generally, the interest coming from the market seems to be for these techniques to be used with carbon fiber composites. There is a big price difference between the machines required for filament winding and tape laying. Generally tape laying machines are much more expensive (can exceed $1,000,000) than filament winding machines (can be less than $50,000). Generally, software is priced with some relationship to the attendant hardware involved in the overall system. Consequently, what software currently exists to support the OLP problem is generally more expensive for tape laying machines.

2.2 Potential Applications

Interest in the use of "traditional" filament winding and tape laying techniques for the manufacture of some types of plastic materials seems to be growing. The automotive market has been big on plastics for quite a while (and not so big on carbon fiber composites) so this evolution could enlarge the market for these techniques considerably.

A new technique sometimes called simply "fiber placement" is gaining in popularity [8]. Fiber placement is essentially filament winding in which the tangent length is zero so that the payout eye (usually adorned with a roller) rides on the surface of the mandrel and can apply some pressure to compact the fibers onto the surface. This extra compaction pressure allows fancy paths to be traversed because the restriction of following geodesics is somewhat reduced. Along with fiber placement techniques come fiber dispensing heads which are capable of adding and subtracting the number of fibers being dispensed so that the band width being applied is variable. This very powerful technique will also require fancier pattern planning software to properly take advantage of the capability.

Some industries are considering the use of the industrial robot as a tape laying or fiber placement machine. To do so, a "tape laying end-effector" must be carried by the robot. Such tape laying heads are often quite heavy and bulky, which then implies an oversized robot needed to manage them.

Overall, the percentage of advanced composite parts manufactured by automated techniques is quite small. Many composite parts are currently manufactured by "hand layup" in which sheets of pre-woven material are placed by hand over forms. If the technology reported in section 1 of this paper becomes more widespread, the percentage of parts which are produced by automated means may increase.

Quite apart from attempting to convert manufacturing techniques from hand layup to machine-based, there is room for new technology to be developed which will aid the hand layup process. Some groups are investigating computer systems which assist the human worker by prompting (and possibly displaying on a screen or projecting onto the part itself) the next piece to be placed.

3. Limitations of Current Technology

OLP systems for automatic composite manufacturing applications are in their infancy. The field is characterized by the lack of standards, a great deal of custom designed machines and tools, and other signs of a technology in its early stages.

In this section we take a stab at naming the top 10 problems faced in the continuing development of OLP systems for automated composite manufacturing. This list also serves as a summary, as most of the entries relate back to the material discussed in the previous sections:

1. Pattern generation on complex shaped mandrels. Much of the available software only deals with simple cases like surfaces of revolution. This would increase the number of parts which could be economically manufactured by filament-winding techniques.
2. Pattern planning for fiber placement techniques in which the band width may be varied. This would fully exploit new hardware under development and improve cost-effectiveness of fiber placement systems.
3. Pattern generation for layup—surfaces with many cut-outs and odd contours. This would reduce had trim work, often required now.
4. Automation for broad goods—much of the composite usage is outside the realm of filament winding, fiber placement, or tape layup. This would help bring a higher level of automation to a large market segment.
5. Ease of use and cost of an OLP system. Currently relatively difficult to use and relatively expensive. This would allow "shop floor" personnel to program composite-manufacturing automation.
6. Interfaces from OLP planning systems to stress analysis packages for more integrated design-to-manufacture systems. This would reduce the overall time and cost of designing and producing composite parts.
7. Optimization of fiber directions and patterns so as to minimize tape filament strain while meeting stress requirements. This would result in higher quality parts.
8. Integration of part design into the OLP system so that parts can be designed such that they are easily manufactured using composite materials. This brings manufacturing know-how to the designers to yield a more effective and inexpensive design.
9. Effective means of dealing with many custom designed machines and material dispensing systems. This would allow software vendors to reduce prices in the face of many one-of-a-kind hardware setups.
10. Development of standards for programming languages and techniques for programming layup equipment. This would ease the factory integration problems when machines and software from multiple vendors are utilized.

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Identifying the Barrier Issues in Composites Applications

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This chapter identifies some of the questions that need to be answered and issues that must be addressed before composites can reach their full use potential. These include design, environmental/safety issues, materials characterization and data standards, computer hardware and software, and education. Both current needs and future opportunities are explored.

Key words: characterization; degradability; design; education; environment; manufacturing; public policy; recycling; standards; testing.

1. Introduction

The widespread use of composites may not be as inevitable as was once thought [Beardmore 90]. Problems that are at once technical, cultural, social, and political combine to replace feelings of the inevitability of the composites revolution with a more pragmatic outlook.

Composites, of course, offer attractive properties in combinations not often found in traditional materials—light weight, durability, strength, diversity, the ability to tailor the material to the end use, and resistance to high temperatures, pressures, and corrosion. Thus, it is not surprising that composites research has tended to focus on technical issues, including improved processing/manufacturability, repairability/maintainability, and performance, as well as lower costs. This research is essential for the commercial growth of composites. But it is in the areas where these purely technical issues interact with cultural, social, and political ones that research and development must not neglect. The following sections will discuss issues in some of these areas.

2. Design

Composites open up both possibilities and problems in the design area. Concurrent with the materials revolution are revolutionary changes in design and product development, manifested by the adoption of Japanese and other international design and management practices on the part of industry and government. The current Total Quality Management (TQM) movement in the defense industry is evidence of this revolution. It is also manifested in the proliferation of terms such as *simultaneous engineering, concurrent engineering, design for assembly,* and *design for manufacturing* in the engineering literature and popular press.

However, these two revolutions are proceeding somewhat independently of each other. This is not only alarming but also surprising, since advanced materials are tailor-made for the philosophies and methods of the design revolution, i.e., the team approach—early integration of all relevant disciplines, rapid prototyping, customer-driven products, shortening of the design cycle, and so on. There is growing evidence that these manifestations of the design revolution are not being adopted by the advanced materials community nearly as quickly as they are in more traditional arenas. The continued success of advanced composite materials is dependent not only on such factors as the development of low-cost automated manufacturing technology, but also on the adoption of the philosophies and methods of the design revolution. Without these benefits, composites may not be able to compete in the long term with other materials systems in terms of cost, quality, and delivery.

While some have argued for a more global definition of engineering design as the information needed to create, use, and dispose of an artifact [Westerberg 1987], in practice the term *design* is often used in a very narrow sense. Rather than integrating activities as it should, *design* often serves to segregate such elements as product definition, interaction with customers, and planning in the areas of processing, maintenance, and product disposal.

However, such activities cannot in general be separated from the more traditional design components of problem analysis, synthesis of alternatives, and evaluation of alternatives. Design is the embodiment of the engineering method, which is defined as the process of making the best change in an uncertain situation within the available resources [Koen 1985]. There is currently a lot of talk about manufacturing competitiveness and how critical it is to economic competitiveness. Manufacturing engineers say, "Pay attention to me." But it is design as the embodiment of the entire engineering process that must balance all the conflicting issues, including manufacturing. If it cannot be described to the factory, it certainly cannot be built right. The critical reason for the adoption of a global viewpoint is that the decisions in the design process are coupled; that is, decisions influence each other. For example, a customer's desire to travel between locations within a certain amount of time might result in the decision to set the cruising speed for a new aircraft at a given level. This decision will affect other decisions on the type of aircraft and its materials of construction, which will affect manufacturing decisions, maintenance decisions, and of course economic decisions. Changing any one of the decisions is likely to have repercussions on a great many of the others. In most cases, few of these decisions exist in a vacuum. Accepting the global viewpoint is one thing; putting it into practice in industry is quite another. The art of practicing the global viewpoint of design will be referred to herein as concurrent engineering.

Modern design efforts are in trouble, especially in the United States. The search for a scapegoat has taken on historic proportions. Some of the candidates are unfair trade practices, inferior and deteriorating work ethics, wage scales that are out of proportion, usurious labor unions, and inhomogeneous cultures [Costello 1988]. A small but vocal minority, however, is trying to spread the message that a large part of the problem is inferior engineering design practice, particularly the early stages of that process:

> Concerned technocrats can continue to reinforce each other about the design issue; however, the attention of the leaders of major corporations, major universities, and major government offices will be required to repair the broken infrastructure of Quality Design Engineering, the Missing Link to U.S. Competitiveness [Bebb 1989].

Bebb [1989] recommends action items for industry, government, and academia to improve design and product development practices. For industry, he contends that senior management must first recognize the design problem. Then, the best design processes in the world must be benchmarked and adopted. Government can help by striving to place design engineering on the national competitiveness agenda and establishing a National Institute of Design. The academic world must elevate design to an honorable position among disciplines, increase design content in graduate and undergraduate curricula, establish strong funding channels for design research, and aid in the benchmarking and improvement of the best design practices.

Bebb's own company, Xerox, has been at the forefront in implementing many of these changes. Their strategy has been to implement sweeping changes in management, corporate structure, corporate goals, and engineering design practice. It is instructive that the answer to highly complex global competitiveness issues do not lie entirely in engineering design, or more accurately, that what is wrong with engineering design can only be corrected with concomitant changes in management and corporate structure. There is, however, plenty of work to do in the design arena itself.

Advanced materials research has tended to focus not on such systems level issues but on specific tools. The reason for this is the same as the reason that design decisions are often arbitrarily separated in practice: it is much easier to be quantitative about individual decisions if it is assumed that the decisions are uncoupled. The tendency to separate design decisions, in essence making them as if they did not depend on each other, is nearly irresistible.

It is driven by many factors: among them, the size of modern development projects, the number of people involved, the complexity of the various decisions attended by the need for specialists, human nature, and modern educational systems.

For instance, it has been shown [Cross 1984] that as design complexity increases, designing (analysis, synthesis, and evaluation) begins to separate from making (manufacturing). As projects become even larger, compartmentalization and specialization increase. The "walls" that have grown up between the decision-making functions in various organizations have become part of corporate folklore. The consequences of such a product development practice are products that require too long to reach the market, cost too much, and often do not adequately perform wanted or needed functions.

Design practices such as concurrent engineering have been identified as state of the art [Newsome 1988]. The rationale for research in these techniques is that the traditional methods of developing products suffer from lack of information of the later stages of the process when the early decisions are made. To return to the hypothetical aircraft, the decision to set cruise velocity might lead to the development of detailed designs for which suitable production methods do not exist. This would likely lead to staggering losses in lead time and project resources. This problem could be avoided if the development team making the early decisions included a specialist on manufacturing processes.

The motivation to invest heavily in concurrent approaches to early product development decisions is shown graphically in figure 1. This curve indicates that up to 70% of the total life cycle costs of projects are committed by the time of the traditional preliminary design review. Thus, the early decisions lock in these life cycle costs, and the detail work of later development stages (traditional design) are practically helpless to correct any early mistakes.

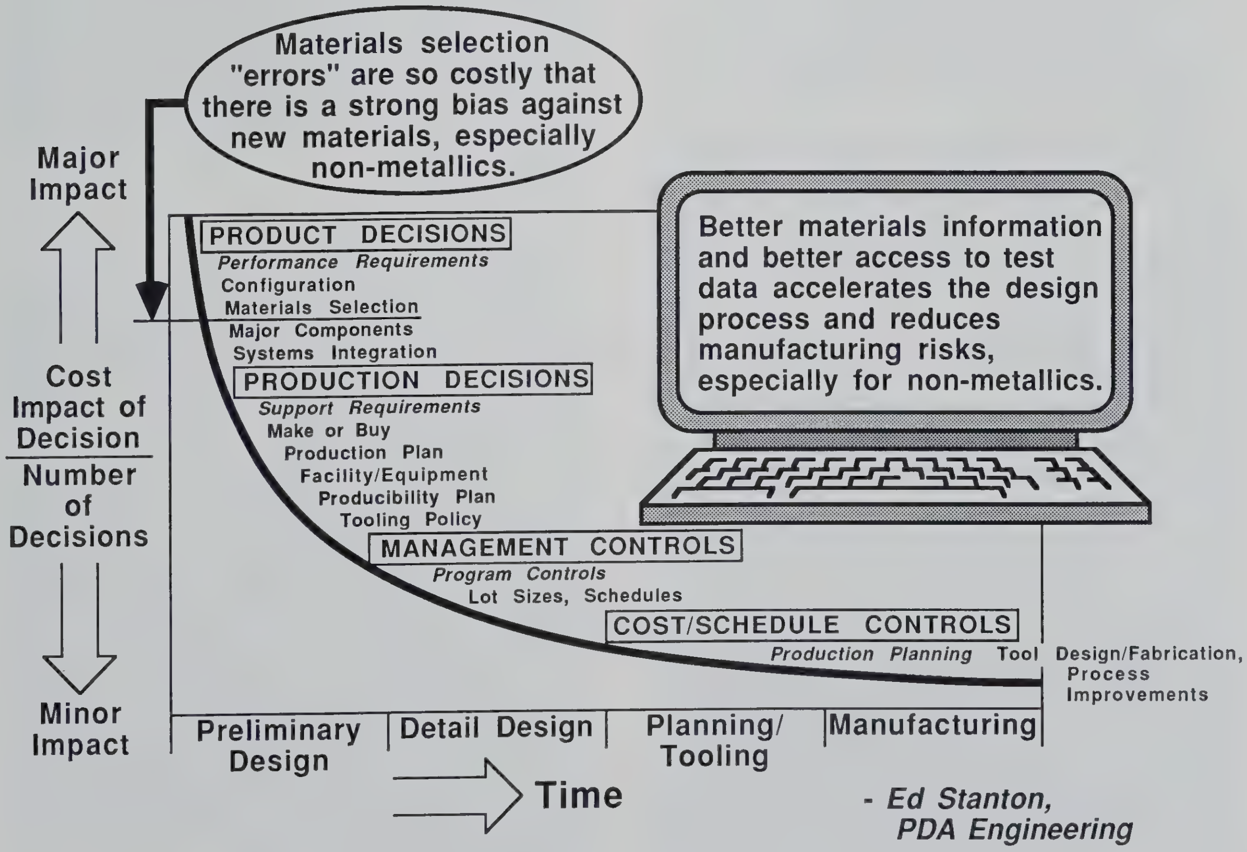


Figure 1. Criticality of early decisions.

A number of weaknesses in traditional (non-concurrent) approaches to product realization have been described. These include lack of knowledge of various later stages of the product development process brought about by lack of communication, and resulting in costly redesign at the intersection of the stages. Also included is the slowness of traditional processes, as measured, for example, by the time between generations of a product. Takeuchi and Nonaka describe the sequential approach to product development as follows:

> Under the old approach, a product development process moved like a relay race, with one group of functional specialists passing the baton to the next group. The project went sequentially from phase to phase: concept development, feasibility testing, product design, development process, pilot production, and final production. Under this method, functions were specialized and segmented: the marketing people examined customer needs and perceptions in developing product concepts; the R&D engineers selected the appropriate design; the production engineers put it into shape; and other functional specialists carried the baton at different stages of the race [Takeuchi 1986].

A number of common misconceptions about concurrent engineering exist [Winner 1988]. The first is that it is a magic recipe for successful product development. Another is that concurrent engineering means simultaneous design and production. Finally, there is the misconception that concurrent engineering is just another specialty that will have its expert on the product development team, to go along with specialists in materials, maintenance, and so on. That is perhaps the most dangerous misconception of all, since concurrent engineering is a systems approach that must have support from the very highest levels of an organization down to the lowest.

Industry and academia have shown a great deal of interest recently in the concepts and techniques of concurrent engineering. There are numerous examples of industrial attempts at concurrent engineering [Winner 1988, Meyer 1979], as well as of attempts at developing systems for performing concurrent engineering [Buckley 1987, Zumsteg 1986]. The industrial case studies feature as many failures as success stories. The failures can be traced in many cases to the common misconceptions about concurrent engineering mentioned above. In other cases, it is difficult to evaluate to what extent a given methodology was responsible for the success or failure of a project. This is because so many factors, such as timing, personnel, changes in the world economy, and even luck combine to determine a project's outcome.

The product development community, lacking specific skills for materials such as advanced composites, has too often attempted to apply the sequential design methods typically used with more traditional materials. However, composite materials exhibit a high degree of coupling among many of the most important decisions such as materials and manufacturing processes. Composites manufacturing is a materials transformation process. This distinguishes composites from commodity alloys, from which parts can be machined, welded, or forged from standard shapes. Such operations are seldom available for composites, nor are commodity shapes often available. The nature of composite materials makes it unlikely that they will ever be successfully designed with in the uncoupled way that conventional materials often are. The composites community is well aware of the highly coupled nature of composites, as is apparent from the conclusions of an industrial survey stating that the ability to "interact" effectively with design and manufacturing engineers was the most important competency required of the "composites specialist" [Lange 1986].

2.1 The Design Triumvirate

The existence of a "design triumvirate" of materials, configuration, and manufacturing process has been noted by several observers [Blundell 1988, Henshaw 1988]. The triumvirate is shown graphically in figure 2.

The idea behind the design triumvirate is that any design decision one can name is related to at least one of the three elements in the triumvirate. Therefore, when these three elements have been completely specified, the design will be complete. The design triumvirate has particular utility in the conceptual stages of a product development project. For composites, there is an added complication in the configuration element of the triumvirate. The added complication is the microstructure, which when taken together with the shape of a part, is defined as the configuration. The following paragraphs deal with the three elements of the composites design triumvirate.

2.1.1 Configuration As stated above, the configuration of a composite structure is defined as the

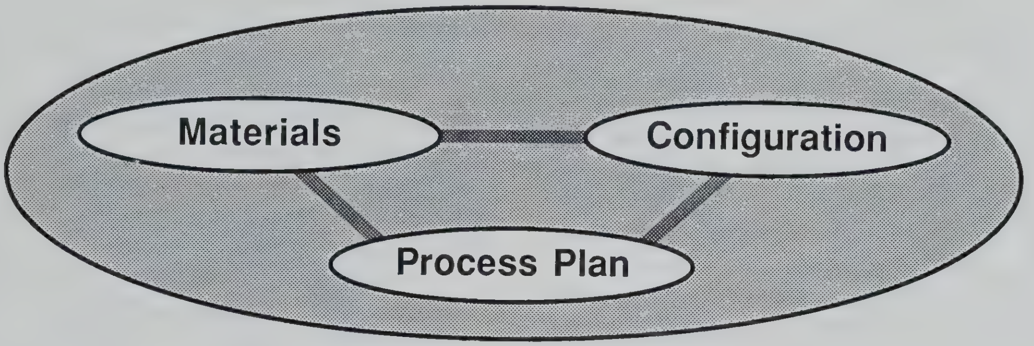


Figure 2. For composites, design choices are physically coupled.

combination of its shape and its microstructure. Traditional designers dealt (almost exclusively) with the shape of their product. However, the idea of designing a microstructure is not entirely unique to composites. For example, designers of metal structures can specify heat treatments that will improve the microstructure of their material, or joining methods that can deteriorate the microstructure. But these changes are at least an order of magnitude less important than microstructural design decisions are for composites.

2.1.2 Microstructure The term microstructure has a somewhat different meaning for composite materials than for traditional engineered materials such as metal alloys. For composites, microstructure typically refers to the geometry (e.g., length, diameter, degree of fiber curvature, etc.), and orientations (with respect to local and global coordinates) of the reinforcement phase(s) in the matrix material as well as the volume fraction of the constituents. The microstructure of a composite determines to a large degree its performance in terms of mechanical, physical, environmental, economic, and other properties. Most aspects of the microstructure are usually created as the part is being formed into its final shape.

For composites, the specification of microstructure is almost always closely coupled to materials, shape, and manufacturing process decisions. That is, the microstructure can rarely be independently specified. For example, one design case study [Kedward 1985] deals with the design of a semitrailer truck frame rail (to replace the steel I-beam that runs the length of the truckbed). The case study proceeded to design an optimum microstructure (continuous fiber layers of a given volume fraction of fibers with each layer oriented at a specific angle in relation to the structure) for the component in order to meet the stiffness and strength requirements of the truck. Later, the decision was made to use a "low-cost pultrusion method" of manufacture, since truck frame rails are common items and many units will likely be required and because the composite rails will have to compete with relatively inexpensive rolled steel rails. However, the ability of the chosen manufacturing method to create the microstructure as designed was not even speculated upon (as it turns out, as of this writing, pultrusion is highly unlikely to create the microstructure as designed). In another case, engineering students working on a design project to build a composite ladder discovered that their optimum microstructure, designed in great detail, could not be fabricated except by manual tape layup, a time-consuming, labor-intensive, low-volume process. They then decided to have two designs, one optimized for mechanical performance, the other optimized for ease of fabrication!

2.1.3 Materials Materials choices are perhaps the most self-evident of the three members of the design triumvirate for structural composites. Most designers are better able to make sound materials judgments than, for instance, manufacturing process decisions. At the most fundamental level, composite materials consist of one or more reinforcement phases held together by a matrix phase. The various phases are mechanically combined to form a heterogeneous material.

The product development team that wishes to make use of composite materials faces the choice of a matrix material, one or more reinforcements, additives and fillers. There are a seemingly endless number of composite materials with seemingly limitless potential. The number of materials with the maturity to warrant selection by the typical product development team is far shorter, however. In many cases, this lack of technological maturity is due to the unavailability, unreliability, or inefficiency of manufacturing processes.

2.2 Manufacturing

Because the various manufacturing processes for composites are so limited in the shapes and microstructures they can create and the materials they can utilize, manufacturing process selection is much more critical for composites than for most traditional engineering materials. Composites manufacturing is a materials transformation process. As with more traditional materials, manufacturing processes for composites consist of a series of steps or stages. Examples of such steps are raw material production, primary material production, primary and secondary shapemaking, post-processing, and joining. Within each step, there are a number of choices (including the possibility of skipping the step). Thus, one can create a chart consisting of manufacturing steps and the options within each step. Such a chart has been referred to as a manufacturing chart [Henshaw 1989]. If one could catalog each of the steps and all of the various options within each step, then by selecting one option from each step, any possible manufacturing scheme (along with a great many impossible ones) would have to come from that chart. Since composites is a young technology, there are relatively few options within most of the manufacturing steps. It is not hard to create a reasonably complete manufacturing chart (table 1).

A manufacturing chart allows one to look at the spectrum of possibilities for creating a composite structure. It also allows one to compare those possibilities in terms of the numbers of steps, the presence or absence of certain steps, and the desirability of various options in terms of customer wants and needs such as cost, repeatability, and time. A manufacturing chart also can serve as a valuable aid to concept generation in product development.

It is not always necessary or even desirable in the early stages of product development to define a manufacturing scheme in terms of each of the stages. It is important, however, to define a manufacturing scheme well enough to ensure that the coupling among the three elements of the triumvirate is accounted for. One way to do this is to consider just the primary materials and shapemaking steps in the manufacturing chart. This simplification has advantages for the early stages of product development. For instance, in the initial stages of concept generation it is often the case that only a single member of the triumvirate need be specified. If it is manufacturing that is being specified, it can normally be so specified by the primary shapemaking method. In certain cases, the primary materials form may also be required.

A second advantage to simplifying the composites manufacturing chart to primary materials and shapemaking in the early stages is in terms of process discriminators. Process discriminators are early decision parameters that allow some differentiation among primary shapemaking processes at the conceptual stage of design. For composite materials, there appear to be relatively few parameters that discriminate among various processes [Henshaw 1989] as shown in table 2.

Theoretically, each of the discriminators divides the set of all feasible primary materials and shapemaking combinations into two sets: those that can provide the requirements of the discriminator and those that cannot.

The shape discriminator is concerned with the ability of various processes to produce basic geometric shapes. For example, certain shapes cannot (currently) be filament wound or can be wound only with great difficulty. The shape discriminator can obviously be dealt with on many levels. For example, the process might someday be automated with expert systems and geometric reasoning to determine the ability of a given process to produce the shape. (Geometric reasoning encompasses elements of machine vision, spatial reasoning, and extracting feature information out of shapes [Westerberg 1987].) At the heuristic level, manufacturing experts can be called upon to judge whether the proposed shape concept is a likely candidate for a given process.

Initially, the microstructure discriminator deals with the issue of aligned versus non-aligned fibers. This normally separates processes such as injection molding and SMC (sheet molding compound)/compression molding from the other processes. Surface finish usually deals with the ability of a process to produce a Class-A automotive finish (although this is not limited to the automobile industry). Service temperature discriminates among polymeric matrix materials and their varying abilities to withstand various temperature ranges, rates of change, and excursions. This discriminator not only differentiates between thermosetting and thermoplastic matrix materials in terms of their manufacturing processes, but also within the set of all thermosetting or thermoplastic materials. Geometric envelope refers to the ability of processes to make various size parts. The number of parts to be made refers to the constantly changing economic heuristics regarding a “cutoff” number of parts below and/or above which the process is said to be uneconomical. The thermal expansion coefficient

Table 1. Manufacturing chart for polymer composites

Raw material	Primary material production	Prefabrication	Primary shapemaking	Secondary shapemaking	Curing	Finishing	Joining
Continuous fibers	Weaving	Ply cutting	Thermoset winding	Cutting	Oven	Machine	Bolting
Thermoset polymer	Prepregging	Dry winding (thermoplastic)	Thermoplastic winding	Reshape	Autoclave	Manual trim	Rivet
Thermoplastic polymer	SMC sheet making	Preform placement	Tube rolling	Radio frequency			Welding
	Braiding	Inserts	Hand layup				Adhesive bonding
	Extrude		Machine layup				Co-curing
	Pultrude		Liquid molding				
	3-D textiles		Injection molding				
	Commingled textiles		Spray up				
	Ordered staple sheet		Compression molding				
			Diaphragm forming				

Table 2. Composites manufacturing process discriminators

shape
microstructure
surface finsih
service temperature
wall thickness
geometric envelope
number of parts to be made
thermal expansion coefficient

discriminator refers to parts which require such tight control of thermal expansion properties that they can only be produced (currently) by tape layup.

The ability of the various shapemaking processes to meet the various requirements of the discriminators is of course changing with time. For example, a process such as liquid molding has over the past few years become increasingly to be perceived as being able to produce a Class-A automotive surface finish. Previously, liquid molding processes would not have been considered for applications requiring a Class-A finish, such as auto body panels.

These discriminators are most useful in the concept selection stage of product development. Most of the discriminators, as is evident from their descriptions above, are heuristics-based. This is appropriate since the conceptual stage is characterized by ill-defined dimensions and other parameters that do not easily accommodate traditional analytical methods. As with any heuristics-based endeavor, process discriminators will be subject to constant change and controversy. With respect to the composites process discriminators, it may be only a slight oversimplification to say that one knows what questions to ask, but the answers keep changing! Nevertheless, the following specific examples of the use of each discriminator is offered in an attempt to show how process discrimination for composites is accomplished at the conceptual level.

2.2.1 Shape A good example of the use of the shape discriminator, in addition to the filament winding example given earlier, is that of pultrusion. Pultrusion is still thought of as being generally applicable only to parts with a constant cross section.

2.2.2 Microstructure A composites manufacturing process can be related to microstructure by its ability to provide three parameters: volume fraction, flexibility, and repeatability. Some processes (injection molding, for one) are severely limited as to the volume fractions, and thus the mechanical and physical properties, they can provide. Flexibility refers to the ability of a process to supply what-ever orientation schemes might be desired. For many shapes, tape layup methods provide almost unlimited flexibility. On the other hand, circumferential filament winders are thought of as being limited in how close they can come to laying fibers along the axis of rotation (±10% is a common number). Repeatability is the ability of a process to provide the same microstructure in part after part. For example, the microstructural repeatability of the SMC/compression molding process is generally felt to be lower than that of random mat reinforced liquid molded parts.

2.2.3 Geometric Envelope This discriminator can bound the competing processes. For example, if a part is too small to make by injection molding, it is probably too small to make by any of the other composites processes.

2.2.4 Number of Parts The shifting heuristics of this discriminator make it one of the most controversial. It is of course related directly to the cost to make the n^{th} part in a given production run. For example, injection molders once commonly reported that runs of less than fifty thousand parts were rarely economical. Now, however, they are increasingly willing to take on much smaller jobs, occasionally less than one thousand parts. Similar shifts in numbers are being experienced in the area of liquid molding and SMC parts. In general, composites manufacturers are attempting to widen the acceptable band of production volumes that is perceived for their process.

2.2.5 Wall Thickness This discriminator is related to shape (in fact, shape can probably be broken down into several other discriminators, as well). Wall thickness is singled out because so many processes are limited as to the thicknesses they can create. Injection molded parts with any single thickness dimension over one-half inch are very unusual. The feasibility of filament wound or tape laid thermosetting parts over about one and one-half inches is highly controversial. At present, to be conservative, many thermoset winders are unlikely to take on parts over one inch in thickness. Such parts are likely candidates for thermoplastic winding (a similar-in-appearance but fundamentally different process, that is still in the development stage with few production examples to date).

2.2.6 Surface Finish Surface finish is another discriminator in a state of flux. A good example is liquid molding. Several years ago this process was not thought capable of producing Class-A automotive finishes. Therefore it was eliminated from consideration from such parts as auto body panels. Advances in the process and materials have changed this situation to the point where several manufacturers are now producing liquid molded exterior auto parts.

2.2.7 Service Temperature This discriminator traditionally has determined whether polymer composites in general were feasible (if the operating temperature is too hot, one cannot select polymer composites). It is also useful in terms of the temperature capabilities of various polymeric matrix materials and the processes capable of handling those materials. Certain thermoplastic composites can, in many cases, withstand higher intermittent and continuous service temperatures than their thermosetting counterparts. But a different set of processes characterizes the two sets of materials. Within thermosets, some of the new higher temperature materials are notoriously difficult to process by any method, let alone an intermediate volume process such as liquid molding. In general, as the temperature limits of a material go up, its processability goes down.

2.3 Summary and Opportunities

Table 3 summarizes some of the heuristics of the manufacturing process discriminators. Heuristic aids such as process discriminators and manufacturing tables have some utility in the early stages of development projects involving composites.

The challenge for composites is to develop more and more sophisticated, reliable and timely heuristics, along with other decision aids such as computerized process models that will allow more and more complex decisions to be made with confidence earlier and earlier in the design process.

Tailorability is an integrating concept for composites. Not only are the mechanical and physical properties of composites tailorable for specific applications, but so are their economic and even their environmental properties (see sec. 4). The opportunities afforded by tailorability are great. To take advantage of these opportunities, an integrated approach to composites design is required.

3. Materials Characterization/Data Standards

Characterization is another issue critical to the future of composites. Despite their superior properties, advanced composites will not be able to compete with metals until industry-wide standards have been developed and adopted. This goal will not be simple or inexpensive to meet. There is cur-

Table 3. Process discriminators versus some major composites manufacturing processes

	Tape layup	Fabric layup	Filament winding	Pultrusion	Liquid molding	Injection molding	Sheet forming	SMC
Shape	flat, or gentle curve	more drapeability than tape	surface of revolution	constant cross section	castings	castings	single-curvature	multi-curvature
Microstructure	long fiber, high flexibility	long fibers, less flexible than tape	long fiber, some limits	long fiber, some limits	long fiber, high flexibility	short fiber, flow induced	long fiber, flow induced	short fiber, high variability
Surface finish	good	good	poor	good	average to good	good	good	good
Service temperature	thermoset, thermoplastic	thermoset, thermoplastic	thermoset, thermoplastic	thermoset thermoplastic	thermoset,	thermoset, thermoplastic	thermoset, thermoplastic	thermoset, thermoplastic (thermoset typical)
Wall thickness	thermoset material's limits	thermoset material's limits	thermoset material's limits	thermoset material's limits	thermoset material's limits	0.5 in max	thermoset material's limits	0.5 in max
Geometric envelope	large	large	large	medium	medium	small	medium	medium
Number of parts	very small	very small	medium to large	very large	medium to large	very large	very large	very large
Thermal expansion	excellent	excellent	fair	good	good	fair to poor	fair	poor

rently much replication of testing within the business, with several companies testing the same materials; there is very little sharing of data and no confidence that the results translate from one screening to another. This is extremely costly: $50,000 to $75,000 per material for basic tests and as much as $1.0 to $1.5 million for full qualification [Wilson 1989]. These figures effectively eliminate small businesses from entering the advanced materials arena, but their participation is needed for the development of specialized products. Development of a database of information accessible to all would alleviate this problem.

The issue of testing composites is complicated by the complexity of the materials. Tests developed for metals are often inappropriate for composites; questions such as "Are we testing what we think we're testing?" and "Are the properties we're testing relevant to the ultimate demand?" must be asked and answered. Characterization of advanced composites is also complex because it comprises a large number of varied components: raw materials, prepreg properties, packaging, physical properties, and mechanical properties, all of which impact manufacturability and design.

Collaboration is critical to meeting characterization goals. The Europeans and the Japanese are ahead of the United States in the development of industry-wide standards; the American, Japanese, and European efforts all need to be synchronized. In addition, companies within the United States will have to cooperate with each other and agree on needs. A standardization initiative is underway in this country, with a uniform designation system, a unified testing matrix, a verification methodology, and a standardized database as its basic goals. It has been endorsed by a number of key organizations, including ASTM, SACMA, SAE, AIA, and DOD, but implementation is still an issue of the future [Wilson 1989].

Internationally, there is also an effort ongoing in the area of standards—the Versailles Project on Advanced Materials and Standards (VAMAS). This organization is dedicated to collaboration in 13 areas of prestandards research, which is a prerequisite for establishing internationally recognized measurement standards. Priorities of VAMAS include data generation, data preparation and presentation, and data access. Again, much of this work and these needs are unique to composites because of the novel combinations of properties making up the final materials, the novel processing techniques by which composites are produced, and the rapid pace at which new materials are being introduced to the marketplace [Schwartz and Steiner 1989].

4. Environmental Issues

Few would argue that concern for the environment will not play a major role in both technological and public policy decisions during the 1990's.

> The topic of waste is now a serious subject in every community large and small, urban and rural, rich and poor. The problem is a growing concern to public authorities and it promises to get worse before society develops the political and technological procedures to control it [Smith 1988].

4.1 Solid Waste Disposal

Environmental concerns are leading to the imposition of more extensive and restrictive government mandates on emissions, waste disposal, recycling, and so on. Even without government intervention, however, the demand for better solutions to current solid waste problems has increased as the public becomes more aware of the negative impact being a "throw-away" society has on our quality of life.

The issue is further complicated by misconceptions about environment-related terminology—materials may break down, or "degrade," through biological, physical, or chemical means, any of which may or may not be appropriate for a given application [Andrady 1988]. Inherent in degradability is a shortened product life, a characteristic which must be tailored to the specific use of the product. For example, we may want hamburger packages to break down quickly while car parts last many years. The irony of this situation has been noted by Kelley, "Those of us who have spent our lives making plastics more durable are conducting new research to reverse the very benefits we once touted." [Kelley 1990].

Most recycling efforts have been devoted to unreinforced plastics rather than to advanced composites. There is, however, an effort underway to develop a process for recycling thermosets. A consortium of 11 molders and 15 thermoset plastics suppliers is conducting experiments to investigate the feasibility of using pyrolysis to recycle automotive parts [Vernyi 1990]. This method to date has been applied to process scrap from SMC and compression molding shops. It involves grinding the thermoset composite scrap and then heating it in the absence of oxygen to around 1400 °F. At this temperature, several by-products are created. One is a gas stream that contains enough energy to sustain the heating process, making the pyrolysis process self-sustaining. A liquid stream is also obtained. Potentially, this substance might be used as a fuel or even as the feedstock for thermoset resins. The third pyrolysis by-product is a char that contains the inert elements in the composite: glass fibers and various fillers. These materials, when separated from the remaining charred organic material, could be landfilled (volume and mass are greatly reduced from the original waste product, and the inert materials are not hazardous), or they could be reused in a less-demanding application. For example, the inert scrap from auto body panels could be recycled into auto panels that are not visible to the consumer.

Even if the pyrolysis method is successful, however, there remain problems such as separating and transporting the scrap from the junkyards to reprocessing units [Vernyi 1990]. This is a problem associated with recycling efforts of all types—it is relatively simple with industrially generated wastes and scrap, but more complex and difficult to implement when sorting and transporting are involved.

Long-term solutions to reuse and disposal problems for composites will have to come from an engineering design approach to their use and disposal. This is because of the many issues that influence reuse and disposal decisions. A partial list of such issues include potential markets (and their sizes), environmental issues (toxicity, degradation, and so on), part separability, retention (or its lack) of properties, the recycling industry infrastructure, the potential volume and mass of materials involved, the costs of energy, landfill space, and materials. Thus, a global approach to the reuse and disposal problems of composites is envisioned. All concepts for solid waste disposal fall into four general classes: dumping, burning, conversion/reuse, and source reduction [Rathje 1989]. It is likely that integrated solutions in each of these four areas will be important for current and future composites applications.

4.2 Workplace Safety

Safety in the manufacturing arena is another issue that needs to be addressed by those in the composite materials business. Styrene emissions, for example, are an issue in working with polyester. It is possible to produce materials in ways that will not threaten the health of those working with them, but this is usually accomplished only at a substantially increased cost. New ways need to be identified to meet the goal of affordable workplace safety.

A recent report [SACMA 1989] covers some of the issue involved in the safe handling of advanced composite materials. Like all chemicals, the components of advanced composites are toxic, although they do not represent hazards when handled correctly. Effects can range from acute to chronic toxicity. Acute toxicity, or the harmful effect after a single or short-term exposure, includes local effects on eyes, skin, and mucous membranes. Depending upon how severe the damage is and whether or not it is reversible, substances are classified as non-irritants, irritants, or corrosives. Chronic toxicity encompasses all long-term effects on human health, including carcinogenicity and mutagenicity.

The chemical reactivity of epoxies, urethanes, phenolics, and other types of thermosetting resins used in composites is essential for their cure, but it is this reactivity that has the potential to cause health and safety problems. Proper industrial hygiene procedures are essential to minimize these hazards. The Threshold Limit Value (TLV) of a substance is the level believed safe under daily exposure conditions. They are recommendations made by the American Conference of Governmental Industrial Hygienists (ACGIH), intended for use as guidelines for good work practices. Permissible Exposure Limits (PELs), on the other hand, are issued by the Occupational Safety and Health Administration (OSHA) and are legally binding.

Routes of exposure when potentially hazardous materials are used include skin and eye contact, inhalation, and ingestion. A variety of controls can be used to minimize these hazards.

Administrative controls, provisions made a company's management, cover handling of material, training, isolation of operations, personal protective equipment, personal hygiene, warnings and labels, housekeeping, dispensing and storage of chemicals, and emergency instructions. *Engineering controls* refer to plant layout, design, and use of equipment. Personal protective equipment should be considered a supplement to such approaches as ventilation systems and closed-system processing in protecting employees from exposure to potentially hazardous substances. *Operations/process controls* are techniques used during the actual processing operation—resin mixing, curing, and handling of cured resin systems—to minimize exposure.

All of these controls should be combined in a cohesive program to ensure safety in the workplace. Because manufacturing operations vary widely—and because new processes are continually being developed—safety programs must be tailored to the operation. The goal is to ensure that employees know what substances are being used, what potential dangers are associated with these materials, and how to use them properly so that exposure can be eliminated or at least minimized.

Communication is essential in this aspect of composites development. No single source of information exists detailing how to use materials safely in all applications. In fact, the SACMA Task Force begins its report by requesting feedback from readers.

4.3 Summary and Opportunities

In short, composites can be adopted in more high-volume applications only if they can be produced in a clean and energy-efficient manner, if safe yet economical manufacturing techniques are developed, and if the materials themselves can be "properly" disposed of or reused profitably. On the positive side of this dilemma is that composites are already tailored to the end use for such criteria as strength, weight, and tensile properties; it is not a drastic departure to tailor them for environmental considerations as well [Andrady 1988].

5. Computers: Hardware and Software

If the applications of composite materials are to increase and if composites are to become routine choices as structural materials, the ability to execute a detailed design and efficiently convert that design into a manufactured component must become available to the product and process development engineers. The complexity of the material system, combined with the requirement for speed, requires that new computer hardware and software that specifically address these issues be brought online. As the use of the personal workstation for engineering design and analysis grows, concomitant growth in composites software is desirable.

5.1 Hardware

The need for computer hardware in the composites industry is the same as in other industries: more powerful computers for large computational analyses and integrated networks for management and control.

Most of the manufacturing simulation software programs described below will require a large amount of memory and high-speed computational capabilities. Much like dynamic finite element analysis, these simulations follow the manufacturing process as a function of time and can require tens to hundreds of thousands of nodes or more. Today's more sophisticated codes can require tens of hours on supercomputers and hundreds of hours on smaller machines to run. Fortunately, many of these codes will be convertible to "vectorized" code to take advantage of the newer vector processors. Vectorization has been shown to be able to reduce simulation run time in some cases by a factor of two [Gilmore 1990].

5.2 Software

The demands required from future software developments are more specialized than the future hardware demands. The necessity for specialized software is derived from the microstructural complexity of composites. Structural design and analysis must consider the three-dimensional, anisotropic nature of composites on a wide variety of responses, e.g., stiffness/deflection, toughness/impact resistance, corrosion resistance, etc. Manufacturing process development must consider the effects of anisotropic heat transfer, phase changes associated with either chemical reaction (in thermosets) or solidification/crystallization (in thermoplastics), rheological behavior, and other similar phenomena in complex, three-dimensional, time-varying environments. Manufacturing must consider the needs of complex control algorithms that can sense variations in in-coming material properties and adjust the process to maintain the quality of the component being produced.

Features that will have to be common to all software developed for composite materials will include ease of problem set-up, output that is simple to interpret, and complete documentation and technical support. Also desired will be transportability across several computing platforms and, compatibility with other computer codes.

5.2.1 Structural Design and Analysis Composite material structural design and analysis has a long history, evolving from relatively simple "back-of-the-envelope" type calculations to today's state-of-the-art finite element modeling. This evolution must continue, with greater sophistication and ease of use being the guiding principles. Additionally, the advances being made in related design tools, such as feature based design and solid modeling, must be incorporated into the newest commercial software. Two areas which are currently ripe for advancement are microstructural analysis of textile-reinforced composites and design for producibility and optimization.

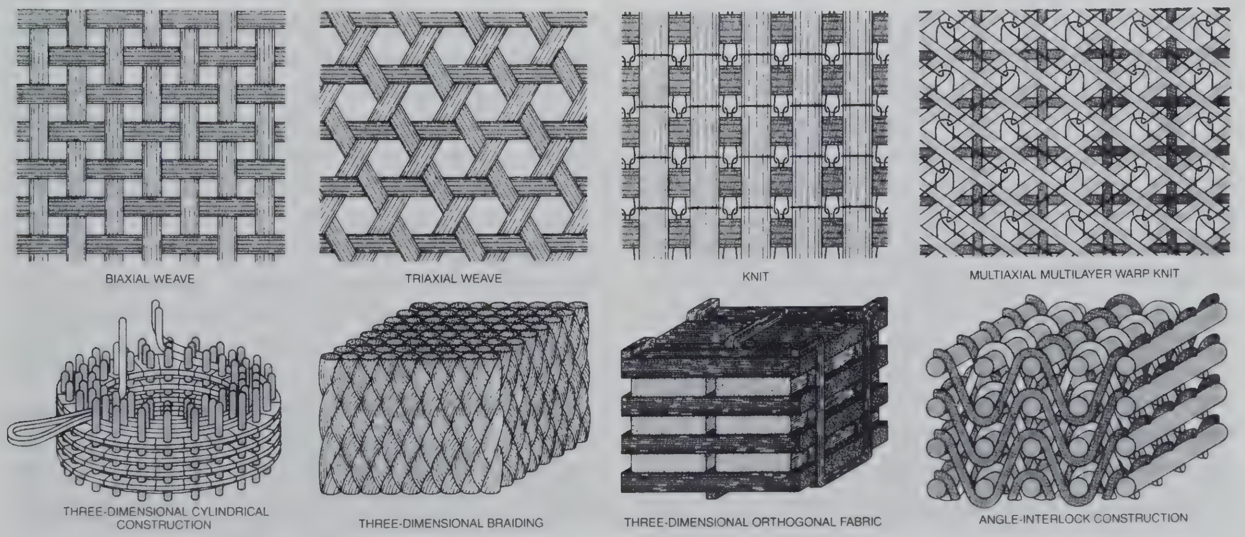
The structural design and analysis of textile-reinforced composites (see fig. 3) is currently available only in approximate form. For example, one commercial code [P/Composite 1987] relies exclusively on experimentally measured material properties to model the behavior of a woven-fabric reinforced composite but has extensive micromechanic models for laminates of unidirectional tapes as well as short-fiber reinforced composites. In these textile-reinforced composites, a woven, knitted, braided, or stitched reinforcement is used to provide increased through-the-thickness properties, especially delamination resistance. Woven reinforcements are used extensively in markets ranging from the high-performance marine market to ballistic applications. Knitted reinforcement has been proposed for a pickup truck box. Braided structures have been used in exhaust cones for rockets and missiles.

In textile-reinforced composites, the microstructure of the reinforcement presents an additional level of complexity in the structural design and analysis. The undulation of the individual fiber tows, whether in a woven, knit, or braided structure, presents major difficulties in predicting not only the strength of the material but also the stiffness and other engineering properties. Some work has been reported on predicting the stiffness of these materials [Ishikawa and Chou 1982, 1983a, 1983b, 1983c] but this has not been integrated into the necessary structural analysis codes to be of general usefulness.

Other features in structural design and analysis software that are desired are the ability to determine "producibility" and design "optimization." The concept embraced by design for producibility is ensuring that the component is manufacturable as-designed. Determining producibility is closely related to the manufacturing process simulation, which is discussed below, integrated with structural and dynamic analysis.

Current design methodologies frequently treat composites in a manner similar to metals. They are often considered quasi-isotropic materials and the ability to tailor the structure's response by using the anisotropic nature of the material is overlooked. Hence, composite structures are frequently overdesigned. There are several possible reasons for this: anisotropic analysis is too difficult, designers are not yet experienced/comfortable with it, insufficient tools exist, the perceived benefit is too small for the required effort, etc. Overcoming this limitation is necessary for many future applications.

5.2.2 Manufacturing Process Development One of the primary uses for computer software in manufacturing process development will be process simulation. Once accurate, verified process simulation codes have been developed they will useful in a variety of applications. An early application will be simulation codes to develop initial process parameter specifications. For autoclave molding, for ex-


BIAXIAL WEAVE

TRIAXIAL WEAVE

KNIT

MULTIAXIAL MULTILAYER WARP KNIT

THREE-DIMENSIONAL CYLINDRICAL CONSTRUCTION

THREE-DIMENSIONAL BRAIDING

THREE-DIMENSIONAL ORTHOGONAL FABRIC

ANGLE-INTERLOCK CONSTRUCTION

Figure 3. Textile reinforcements for composites (after Chou et al.).

ample, this would include temperature ramp rates, hold and soak temperatures, pressure during the cycle, vacuum during the process cycle, and total cycle time. Repeated execution of the computer program would optimize the cure cycle yielding acceptable components in the shortest time. A similar use will be to conduct sensitivity studies to identify the process and material variables that must be accurately controlled to provide a robust manufacturing process.

Another near-term use will be mold design to reduce the number of prototype molds, and mold modifications, that must occur before an acceptable mold results. Using the simulation software, the desired location of mold features such as gates (e.g., to locate weld lines where desired), vents (e.g., to ensure complete mold filling), and heating and cooling features (e.g., to ensure uniform part heating/cooling) can be accomplished without having to resort to trial-and-error cutting of the mold.

Currently, commercial software (e.g., I-DEAS from SDRC, MOLDFLOW, POLYFLOW, and CFLOW) is available for for simulating injection molding process. Current injection molding simulation software is directed at the unreinforced plastics industry. The simulations are typically combined with finite element packages and offer interfaces to structural analysis routines. However, these are first generation codes and are limited in their capabilities. The most severe limitation currently is the inability to predict the location and orientation of the reinforcing fibers and how that is influenced by processing conditions, especially when the full three-dimensional nature of the flow field in complex geometries is considered.

SILMA currently offers a commercial code to simulate the tape-laying process and is expanding it to include filament winding. It simulates the motion of a robotic tape-layer or, in the case of filament winding, a robotic "fiber placement" head to identify potential problems such as excessive overlaps and/or gaps as the tape is being placed onto a surface. The data developed during this "off-line" design is then used to generate control data for the tape-laying or filament winding robot. This code, like the injection molding simulations, is limited in its capabilities. Since it is primarily a path simulator code, it does not include any other processing information, such as degree of cure, temperatures, development of residual stresses, etc. Clearly, interfacing the output from this, or similar, package with an analysis program would provide a unique opportunity.

Manufacturing simulation programs are being developed for many other processes. An extensive amount of work has been reported in the literature on modeling the autoclave process [e.g., Bogetti 1990], compression molding [e.g., Jackson et al. 1986], pultrusion [e.g., Batch 1989, Han 1986, Hackett 1989], RTM [e.g., Michaeli et al. 1989, Claus and Loos 1989, Molnar et al. 1989], S-RIM [e.g., Eckler and Rust 1987, Liou et al. 1989], and thermoplastic sheet forming [e.g., Beaussert 1990]. Undoubtedly, there are additional, unreported efforts ongoing that are proprietary to the developers. Each of these programs has features that can provide some assistance to a process development engineer. However, these codes are not currently commercial and, therefore, most likely lack, at least, the necessary documentation and technical support to be useful in an industrial setting.

The most challenging aspect of developing suitable process simulations is incorporating the fundamental engineering science base, e.g., heat transfer, exothermic reaction kinetics/solidification, rheology (flow through porous media, flow of highly filled suspensions), into an analysis scheme that permits the engineer to account for the three-dimensional anisotropy of these materials. Furthermore, these phenomena must be coupled within the analysis, e.g., the effect of a temperature rise on the viscosity and the reaction rate must be included as well as the effect of an exothermic reaction on the temperature.

Once such process simulations are developed they will, of course, be no better than the input data used to characterize the material components. Therefore, as more sophisticated process models become available it will be necessary to be able to quickly and easily obtain the required input data. It also requires that the constitutive equations used to describe the material behavior accurately represent the material over all of the conditions it encounters during the process cycle. Another need will be incorporation of the appropriate microstructural modeling algorithms to predict the stress-strain response of the "as-manufactured" material.

The second challenge in developing process simulation codes is identifying the appropriate output. The minimum output that is required is the state of the material during the processing cycle. For example, the point-wise degree of cure, void content, pressure, and temperature would be necessary. For processes involving flow of material (e.g., injection molding, compression molding, RTM, S-RIM, and RIM), the location of the flow front during the process cycle must be provided. In processes where there is movement of the fibers (e.g., injection molding, compression molding, and thermoplastic sheet forming), the orientation of the fibers must be tracked during the process. As the sophistication of the process models increases, estimates of the residual stress, process induced warpage, and other material properties must be considered.

The third challenge in developing useful simulation codes is developing tools for displaying the input and output in a usable manner. This requires incorporation of high-level, preferably color, graphics into the program.

Also useful would be an interface to standardized databases of material properties (this may require that specialized databases of processing related material properties be developed). Other useful interfaces would be to the structural design and analysis programs. Under this scenario a designer would use one package to develop a preliminary shape. This shape would then be "made" by the process simulation model. Once proof-of-manufacturability had been demonstrated and the pointwise microstructure determined, the component could be analyzed to ensure satisfactory structural performance. These three computer codes, shape design, process simulation, and structural analysis, will most likely be separate modules and complete interchange of data among them will be necessary.

5.2.3 Manufacturing Process Control For composite manufacturing processes to become fully automated and for consistently acceptable components to be produced, it will be necessary for more advanced process control algorithms to be developed and implemented. Two possible approaches to process control include artificial intelligence and the newer concept fuzzy logic. Concomitant with development of these approaches will be the requirement of new sensor technology.

Recent progress has been made in applying artificial intelligence principles to autoclave curing process control [Park and LeClair 1987 and LeClair et al. 1989]. Successful processing of an aged material (not processable by the conventional cure cycle) has been reported. The current limitation to this approach for process control seems to be the speed and accuracy with which it can respond to variations in the process. In autoclave control, adjustments could be made only every few minutes. Since the process itself required several hours, this was acceptable. However, for faster process, such as injection molding and resin transfer molding (which take a few seconds to a few minutes) this is much to slow.

Fuzzy logic presents a new approach for process control that has two important features for composites processing: (1) it allows for uncertainty and imprecision in the data and (2) it is a "self-teaching" or "self-optimizing" scheme much like artificial intelligence. The paper that introduced fuzzy logic was published in 1965 [Zadeh 1965]. This approach has been extended to process control by Xiangchu and Chengyuan [1988]. Actual applications of fuzzy logic to process control have been mentioned by Rogers and Hoshiai [1990]. Though still a few years from commercial application, this technology could be of significant value to the composites manufacturer.

Regardless of the approach used for controlling the manufacturing process, it will most likely also require new sensor technology to be developed. Current sensors can easily monitor gross process conditions (e.g., temperature, pressure, velocity, etc.). However, new techniques are needed to measure degree-of-cure, viscosity during processing, residual stress development, etc. The necessary hardware and software to connect these sensors to the process controller must be developed. It is also possible that a new field, mold instrumentation, will develop that will specialize in specifying and locating sensors in "intelligent" molds and processes to be used by the advanced process control algorithms.

5.3 Summary and Opportunities

The opportunities in developing new computer hardware and software for the composites manufacturing industry are vast and varied. In addition to the need for larger, faster computers to perform manufacturing simulations, smaller units designed for process control are needed. The developments in software are also wide ranging. Large, complex codes will be needed by designers and process development engineers while smaller and less complex algorithms need to be developed for the manufacturing shopfloor for use in process control and data acquisition.

6. Education

Education is a key area that has to be addressed, especially in the United States. The specific problems of advanced materials that relate to education are simply a subset of the general educational crisis in the United States today. It appears that American students are no less intelligent and American teachers are no less skilled than those in Europe and Japan. However, the American educational mission differs from those of Europe and Japan. Schools in most other countries do not sponsor sports and, in general, education and the teaching profession are assigned higher priorities elsewhere than in the United States [Milford 1990].

6.1 Secondary Education

Secondary math and science education have to be improved if American students are to succeed in engineering fields at the college level and in technical careers. This need is now characterized by a vicious cycle that must be broken somewhere if the problem is to be solved. Teachers in the United States receive less pay and fewer accolades than their counterparts in Japan and Europe; as a result, fewer good math and science students in this country elect to teach, which fuels the problem of poor secondary education in these subjects. In contrast, Japanese teachers earn more than engineers, and in Germany, teaching is such a highly regarded field that qualified graduates may wait 5 years for an open position [Milford 1990].

6.2 Graduate Education

At the post-secondary level, programs need to be established outside departmental/disciplinary lines so that students receive an integrated rather than a fragmented education. Colleges and universities have traditionally required students to select a departmental major; most people now working in composites were trained in ever-narrowing engineering disciplines that work against the necessities of integration and concurrent engineering discussed above in the design section of this chapter. It is essential that integrated engineering educational programs tailored to the needs of the composites industry be developed to make graduates more qualified to work in industry and to minimize the need for retraining later.

Bank and Dvorak [1987] surveyed the educational and research programs in composite materials in the United States [Bank and Dvorak 1987]. They looked for a number of features in these programs: an interdisciplinary character, a formal center or research group, developed laboratory facilities, nationally recognized researchers, significant student participation in research, and involvement of undergraduates. The survey indicated that although many institutions have research programs in composites, they lack several of the other criteria, rendering them unable to support classroom programs in this area.

6.3 Continuing Education

Even with improved undergraduate-and graduate-level education, however, the need for retraining cannot be eliminated; continuing education is critical in areas where the technology is evolving rapidly. Abelson cites an NAE report which suggests that the half-life of an engineer's skills is 2.5 years in software engineering, 5 years in electrical engineering, and 7.5 years in mechanical engineering [Abelson 1988]. Given the rapid pace of technical advances in composite materials and processing, the half-life of the skills of a composites engineer cannot be very long. As Abelson notes, "With the practice of engineering changing so rapidly, there is a need for lifelong learning."

However, continuing education programs tend to be plagued by problems of two sorts—economic and substantive. First, budgets for retraining are often cut as companies look for ways to reduce costs. Professional development seminars and workshops can cost a company $2500 and up per attendee for a 3- to 4-day course when travel expenses, course fees, and missed work time are factored in [Landis 1989]. As a result of these high costs, the popularity of national courses has declined.

One effective way to fill the gap is through the use of videotape and videodisc technology. Benefits of this approach are that interactive programs tailor the level and substance of instruction to the student, costs are reduced, students can work at their own pace, less time is lost from work, and both videodiscs and videotapes are "visual"—and perhaps therefore more meaningful—ways to learn [Ross 1988]. On the other hand, videotape and videodisc courses are expensive to produce and have an alarmingly short shelf-life, due to rapidly changing technology.

Satellite technology has also assumed a growing role in providing continuing education to large numbers of people at a reduced per-student cost. A recent example of the use of this approach in disseminating composites information was a presentation by the National Center for Composite Materials Research at the University of Illinois at Urbana-Champaign. The series, funded by a grant from the Office of Naval Research, was entitled *Advances in Composites.* The seven broadcasts, each 1-hour long, covered a variety of topics including the interphase in composites, the manufacturing history and structure-property relationships of carbon fibers, compression failure in composites, and experimental analysis of shear strains. The approach enables a large number of people to be reached with the latest information emerging from composites research and development programs. Greater use of satellite technology would enhance continuing education and retraining efforts throughout the world.

Regardless of the medium used, however, it can be difficult to formulate the content for continuing education courses in the areas where they are needed the most; developments in fields like composites can occur more rapidly than curricula can be developed and course materials prepared. Outdated videotapes are no better than obsolete textbooks or 5-year-old lecture notes.

Collaboration can play an important role in developing good continuing education materials. A training program on the edge of a developing technology calls for collaboration between university faculty and corporate engineers as well as an unusual flexibility in the process itself [Monib 1989]:

> The needed expertise for a training program is in the university, where faculty teach engineering fundamentals and where keeping up with new theory and applications is part of the territory, and in industry, where new design and manufacturing processes, software development, and adaptation become the corporate bread and butter.

As one who has formed a composites group from individuals trained primarily as chemists and chemical engineers, Monib is well aware of the pitfalls associated with—and the critical need for—retraining in an area that is at the edge of a developing technology. It is another issue that must be addressed in the effort to better utilize advanced composites.

6.4 Summary and Opportunities

Education in a field that is both interdisciplinary and rapidly changing is complex and challenging. Programs are needed at all levels—undergraduate, graduate, and continuing—to ensure that enough composites scientists and engineers will be trained to meet future needs in the field. Opportunities exist at all levels for improving existing programs as well as for exploiting new teaching technologies as they develop. Satellite courses, videotapes, and videodisc courses can fill gaps left by quickly outdated textbooks and coursework that dates back several years. Short courses, workshops, and symposia can also play an important role in keeping scientists and engineers up to date. Finally, the interdisciplinary character of composites research and education demands that academic institutions lower departmental boundaries, enabling students to select their curricula from a varied menu. More courses that are inherently inter- (or cross-) disciplinary need to be developed to make the composites-related degree more cohesive for the student.

7. Conclusion

Just as there are challenges for specific composites processing techniques, there are also challenges associated with the barrier issues for composites in general. Design, materials characterization and data standards, environmental issues, computer hardware and software, and education are each characterized by significant problems. Solutions to these problems will prove to be varied, but they are share a theme of integration: solutions in one area will require consideration of each of the other areas. For example, the problems in materials characterization and data standards for composites will not be solved without concurrent solutions in education (to ensure properly trained composites engineers), design (to ensure that standards reflect what the customers want), computers (to ensure that the data is properly handled), and the environment (to ensure that the right things are measured and standardized). While some in the composites technical community are addressing these problems, it is clear that more needs to be done to overcome these barrier issues. It is not enough anymore just to be the "stiffest and strongest."

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This monograph deals with a spectrum of composites processing technologies that represent a wide range of technological maturity. Some of the processes (contact/vacuum bag molding, compression molding, and injection molding) have been used for many decades. Others (thermoplastic sheetforming) are at the other end of the maturity spectrum and are still in the development stages. Others yet are seeing a revolution in applications as new materials become available (thermoplastic filament winding and pultrusion) or as new concepts in design are realized (RTM, S-RIM).

The objective of this monograph is to encourage industrial competitiveness of small companies by pointing out potentials for invention, a wide range of opportunities from improving existing technologies to developing entirely new ones.

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